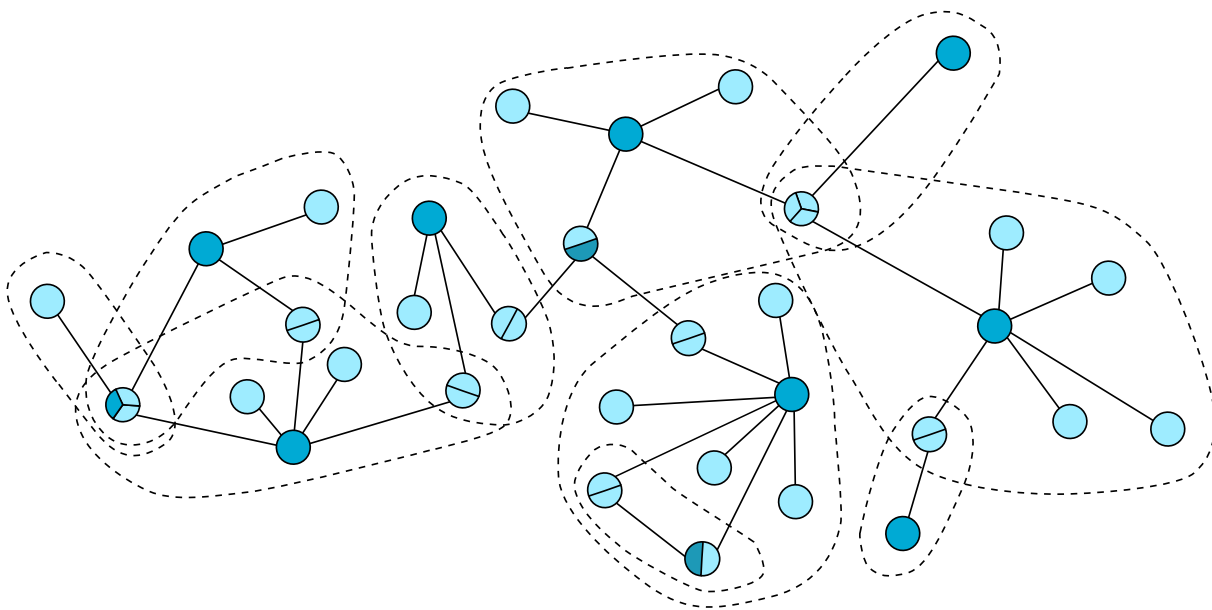

Connectivity Maintenance for mmWave WPANs

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December 15, 2009



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Abstract

Recently the need for ultra high data rate wireless networks has increased. With the improvement of CMOS technologies, 60 GHz WPANs has become more interesting commercially. 60 GHz radio operates at wave lengths in the order of millimeters at a frequency band between 57 and 64 GHz. The 802.15.3 MAC is specified to provide high data rate and also have QoS capabilities. Because of physical properties of 60 GHz radio, humans and other object are sources for blocking and shadowing of the wireless channel. The 802.15.3 MAC does not specify how these kind of connection issues can be solved. To overcome problem of shadowing and blocking, changes have to be made to the 803.15.3 MAC and route discovery is needed in case two node lose their peer-to-peer connection.

This thesis provides a solution for blocking of a connection between two devices in a piconet by using a multi-hop solution. First a route discovery process is initialised. If needed intermediate nodes are used to reconnect the devices. In case either the source or the destination is excluded from the piconet, a new piconet is formed, creating a mesh network. The newly created piconet contains devices which are in reach of the source and the destination.

A measurement for the performance of the route discovery process is the time needed to find the optimal route between the source and the destination. A mathematical model has been derived for route discovery during the CAP using directional antennas. In OPNET Modeler® the route discovery has also been simulated using the 802.15.3 MAC extended with directional antennas. The mathematical models do not exactly produce the same values for the delay as the simulation. However, the mathematical model and the simulations show the same behaviour. Furthermore, both the mathematical model and the simulation show that for small networks initialising a route discovery process is quick enough to overcome blocking.

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Acronyms

ACK	Acknowledgement
ATP	Association Time Period
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CAP	Contention Access Period
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTA	Channel Time Allocation
CTAP	Channel Time Allocation Period
CTS	Clear To Send
DEV	Device
DevID	Device Identifier
DestID	Destination Identifier
HDTV	High Definition Television
MAC	Medium Access Control
MCTA	Management Channel Time Allocation
mmWave	Millimeter-Wave

NbrID	Neighbour Identifier
OOK	On-off Keying
PHY	Physical
PNC	Piconet Controller
PNID	Piconet Identifier
QAM	Quadrature Amplitude Modulation
QoS	Quality Of Service
QPSK	Quadrature Phase Shift Keying
RREP	Route Reply
RREQ	Route Request
RSSI	Receiver Signal Strength Indicator
RTS	Ready To Send
RTT	Round Trip Time
SIFS	Short Inter Frame Spacing
SrcID	Source Identifier
SNR	Signal to Noise ratio
TDMA	Time Division Multiple Access
WMN	Wireless Mesh Network
WPAN	Wireless Personal Area Network
WLAN	Wireless Local Area Network

Chapter 1

Introduction

In the near future the need for ubiquitous wireless networks in home and enterprise environments is expected[29]. During the last few years improvements on the fabrication of Monolithic Microwave Integrated Circuits (MMIC) and Complementary Metal Oxide Semiconductor (CMOS) radio receivers have made 60 GHz Millimeter-Wave (mmWave) communication systems suitable for commercial use[28]. In 2001 the FCC allocated the frequency band of 57-64 GHz for unlicensed use, making it an even more attractive technology. The main reason for using 60 GHz radio technology for communication is the ultra high data rate which can be provided. At 60 GHz the achievable data rate is about 2 GB/s for a simple modulation scheme, where contemporary wireless systems operating at 2.4 GHz achieve data rates of 54 Mb/s using a more complex modulation scheme.[22, 29, 35, 36]

Due to limitation of the transmission range 60 GHz is especially interesting for Wireless Personal Area Networks (WPAN) which cover distances of about 10 meters. WPANs are currently standardised by the IEEE in the 802.15 group. A well known WPAN technology is Bluetooth, currently standardised in 802.15.1. For high data rate WPANs the IEEE 802.15.3 standard is specified. Besides providing a high data rate up to 55 MB/s, this standard also provides Quality of Service(QoS) capabilities to support multimedia data types. Because the 802.15.3 standard operates at a much lower frequency of 2.4 GHz, IEEE assigned the 802.15.3c group to provide an alternative physical layer for the existing 802.15.3 standard. Because of blocking, mobility and other phenomena which affect the channel, the MAC layer of the 802.15.3 standard is not suited for mmWave WPANs. Therefore in order to provide a continuation of service, a new or improved MAC layer with resource management should be applied.[1, 22, 35, 36]

This chapter is organised as follows. In Section 1-1-2 general WPAN properties will be discussed. Important aspects of the 802.15.3 protocol will also be explained. In Section 1-2, 60 Ghz radio properties will be explained. The challenges the mmWave WPAN faces will pass in Section 1-3. This chapter ends with the thesis goal and outline in Section 1-4.

1-1 WPAN Properties

Wireless Personal Area Networks (WPANs) are networks formed by low power devices, which are wireless and have relatively short transmission distances. The typical transmission range of WPAN devices is about 10 meters. Because of the small distance the devices operate in a personal space. There is also little or no infrastructure involved, unlike the case with Wireless Local Area Networks (WLANs), which are able to cover a larger distance of about 100 meters. A typical application of a WPAN is synchronisation and file transfer from a handheld device to a PC.

The IEEE 802.15 working group has as goal to define a standard for wireless communication within a space that typically extends towards 10 meters. The working group focuses on the Medium Access Control (MAC) layer and Physical (PHY) layer specifications for WPANs.[2]

1-1-1 Piconet Topology

A piconet consists of multiple independent devices (DEVs). One of these devices is chosen as the piconet controller (PNC). The piconet controller schedules peer-to-peer communications between the different DEVs. It also provides the basic timing and manages the shared resources according to requests from the various DEVs. Each piconet can have only one PNC and many slaves. A device can only be the PNC of one piconet, but it can simultaneously be a slave in multiple piconets.[10, 30]

A scatternet is a collection of multiple piconets which overlap each other. The devices which are in the overlapped region can be used for communication between the piconets. This allows devices which are outside overlapped areas to be able to communicate with another device in another piconet by using multiple hops. In Figure 1-1 an example of a scatternet is given.[19, 30]

WPANs are standardised in the 802.15 group. Within this group the 802.15.3 standard gives a specification for the PHY and MAC layer for a high data rate WPAN. The mmWave WPAN is also meant for high data rate communication. Therefore re-use or partial re-use of the 802.15.3 MAC is desirable.

1-1-2 Piconet Architecture

The piconet architecture is based on a master/slave concept. In a piconet one device is the master and up to 243 devices are slaves. The master, also called the Piconet Controller (PNC), is responsible for timing and scheduling the communication between the slaves. Apart from this the PNC also manages QoS requirements and power saving modes. The slaves in the piconet can communicate on peer-to-peer basis. Meaning that if a device wants to communicate with another slave, it sends a control message to the PNC to set up

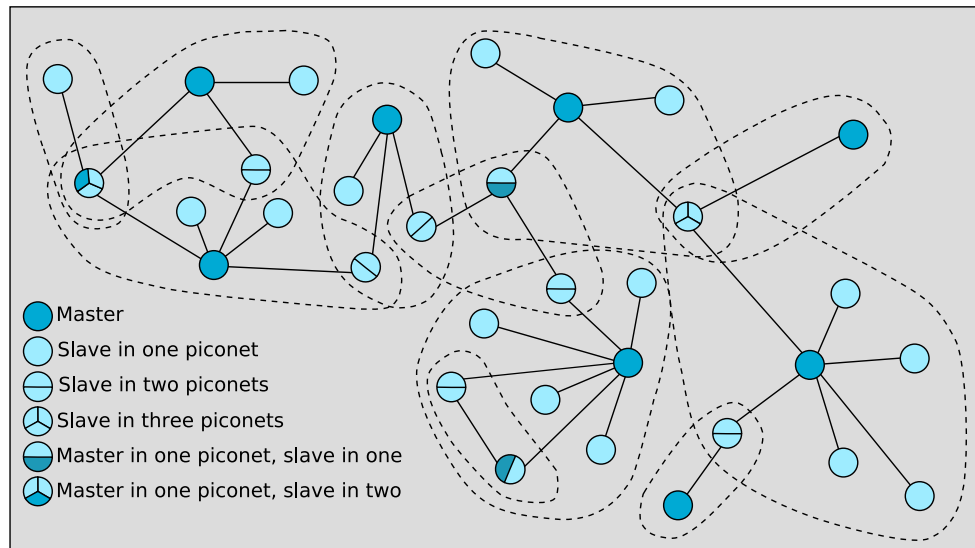


Figure 1-1: An example of a complex scatternet. Note that a device can be slaves in multiple piconets, but can only be a master in one.[19]

a connection between the two devices. Once the communication between two slaves has been set, the master is not needed anymore for further communication.

In order to distinguish the devices in a piconet, every DEV has a DEVID. The DEVID is a number with the maximum length of a byte. Besides the DEVID 0x00 which is always reserved for the PNC, there are twelve other reserved DEVIDs. This means that there are 243 available DEVIDs left for DEVs to connect to the PNC. The DEVID values 0xF7 to 0xFC are reserved for neighbouring piconets (NbrID). Neighbouring and child piconets are further explained in SubSection 1-1-4.[4]

1-1-3 802.15.3 Superframe

Figure 1-2 shows the superframe of the 802.15.3 WPAN. The superframe is divided in three parts, namely the beacon, the contention access period (CAP) and the channel time allocation period (CTAP). The length of the superframe is variable and is determined by the piconet controller. The duration is expressed in micro seconds, with a maximum of 65535 μs (16 bits).

Beacon The beacon is used by the PNC to broadcast control information. This broadcast includes channel time allocations for the current superframe, information for new devices to join the network and power management parameters. The slaves use the beacon to synchronise with the master.

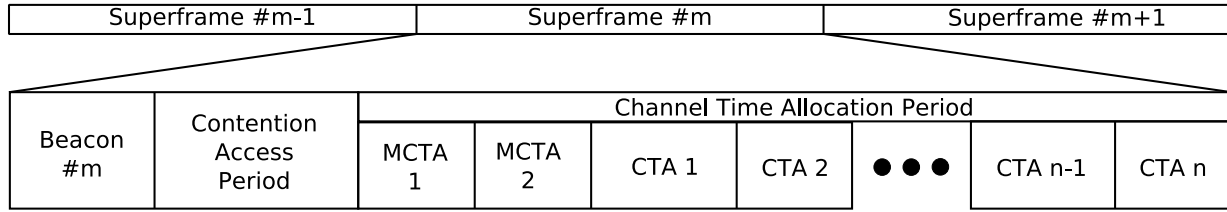


Figure 1-2: The superframe format of the IEEE 802.15.3 standard.[4]

Contention Access Period The CAP is used for transmission of data which does not require QoS guarantees, such as short bursty data, channel time requests, authentication request/response and other commands. The PNC decides how long the duration of the CAP is, and broadcasts this duration to all the devices through the beacon. During the CAP the channel is accessed by using CSMA/CA.

Channel Time Allocation Period The CTAP, also known as the contention free period (CFP), is used to transmit asynchronous as well as isochronous data streams and is used on Time Division Multiple Access (TDMA). Data with certain QoS requirements is transmitted isochronous. The CTAP consists of Channel Time Allocations (CTA) and optional Management Time Allocations (MCTA). MCTAs are used for command frames between the PNC and other DEVS. In each superframe devices can request CTAs for the next superframe to the PNC, which takes care of the allocation. The position of the CTA of a device is not fixed, and may change from superframe to superframe. [4, 7, 24, 30, 38]

1-1-4 Piconet Coordination

To initialise a piconet a device which is able to function as a PNC, scans the available channels to find one that is not being used. When such a channel is found, the PNC starts transmitting beacons, after the channel has been idle for a certain amount of time. The PNC even transmits the beacon if there is no other device in the piconet. When there is no other channel available the device may start a dependent piconet.

A device can join a piconet by transmitting an Association Request command to the PNC. When this command is received the PNC will respond with an Association Response command. When the association is successful this command contains a DEVID for device joined, else it will contain the reason for rejection. After a new DEV has joined the piconet, the PNC will broadcast the piconet information which contains all the features of every DEV in the piconet. Broadcasting the information allows other DEVS in the piconet to become aware of the new DEV, as well as giving the DEV information about the DEVS already in the piconet.

When a DEV wants to leave the piconet or the PNC wants to remove a device, a disassociation process is started. The DEVID associated to the DEV will no longer be valid.

After a waiting period has expired the PNC can use the DEVID for other devices which want to join the piconet. A DEV will be disassociated by the PNC if the PNC does not receive any frame within the association timeout period (ATP). In order to keep a DEV which does not have any traffic to send, connected to the piconet, the DEV may send Probe Request commands. The PNC will then reset the ATP. When the ATP already has been expired and the PNC receives a frame from the DEV, the PNC will transmit a Disassociation Request command to that DEV. If beacons from the PNC are not received by a DEV for longer than the ATP, the DEV will consider itself disassociated and may initialise an association process[4].

1-1-5 Dependent Piconets

When there are no more channels available to form a piconet, a dependent piconet can be initiated. There are two types of dependent piconets: a child piconet and a neighbouring piconet. Dependent piconets depend on the PNC of another piconet. This already established piconet is called the parent piconet. An independent piconet is a piconet which does not contain a dependent piconet.

No device in a child piconet or neighbouring piconet, except the PNCs, can communicate directly to another device in the parent piconet. If this is necessary, routing should be applied. The 802.15.3 MAC does not solve this problem, and leaves the routing of traffic open for higher layers.

Child Piconet

The first type of dependent piconets is the child piconet. In a child piconet, the child PNC is a member of the parent piconet, but cannot be the parent PNC at the same time. Because the child PNC is a member of the child piconet as well as the parent piconet it is possible for the child PNC to exchange data with any device in both piconets. Child piconets can be used to extend the area of coverage of the piconet, or to shift some computational or memory requirements to another PNC capable DEV. It is allowed for the parent piconet to have multiple child piconets. It is also allowed for a child PNC to have another child piconet.

A child piconet has a different piconet ID (PNID) than the parent piconet. Furthermore it acts as an autonomous piconet, where association and security are handled by the child PNC and not the parent PNC. A child PNC communicates within a reserved private CTA of the parent superframe. In a private CTA, the SrcID and the DestID are identical and in this case the DEVID of the child PNC. The arrangement of the superframe of the child piconet within the private CTA of the child PNC is depicted in Figure 1-3.[4]

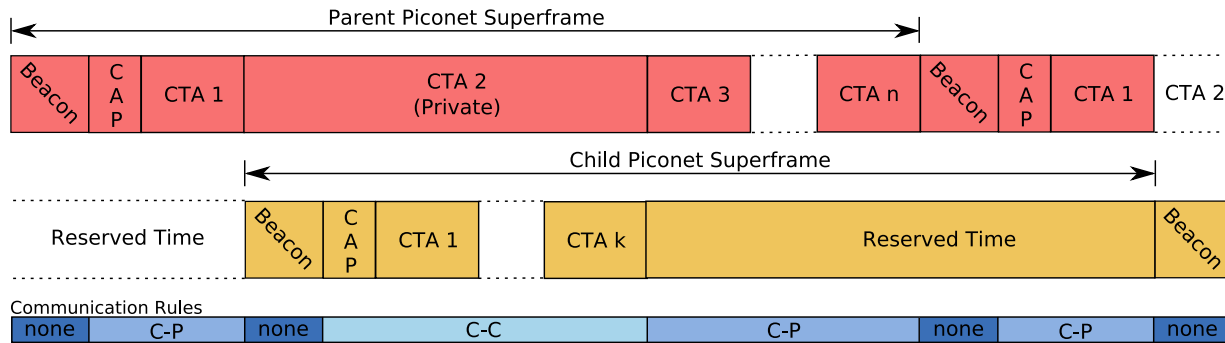


Figure 1-3: The parent piconet and child piconet superframe relationship. During 'none' there is no peer-to-peer communication. This happens during the beacons. The 'C-P' period is when communication between the child PNC and any member of the parent piconet is possible. During the 'C-C' period, communication between various devices in the child piconet is allowed.[4]

Neighbouring Piconet

A neighbouring piconet is the second type of a dependent piconet. The neighbouring piconet is a mechanism to create a piconet if there are no more physical channels available. Unlike a child piconet, where the PNC is a member of the parent piconet, the PNC of a neighbouring piconet is not a member of the parent piconet. This means that during the CTAP of the parent piconet, the neighbouring PNC shall not communicate to any of the devices in the parent piconet, excluding the parent PNC, on a peer-to-peer basis. Furthermore the parent PNC cannot be a member of the neighbouring PNC.

A PNC capable device wanting to create a neighbouring piconet sends an Association Request command, which includes a request as neighbour PNC, to the parent PNC. The parent PNC responds with Association Response command. When accepted the response contains a DEVID for the neighbouring PNC which is an unused NbrID. If the formation of a neighbouring piconet is rejected, depending on the rejection reason code, the neighbouring PNC capable device may try the request at a later time stage.

Like with the child piconet, the neighbouring piconet uses a different PNID than the parent piconet. Also the neighbouring PNC transmits the beacon in an assigned private CTA. The CTA is requested at the parent PNC by using the NbrID as SrcID and DestID. The superframe for a neighbour piconet is displayed in Figure 1-4.[4]

The neighbouring piconet is not restricted to the 802.15.3 protocol. It may also use a different MAC protocol such as 802.11g or the ZigBee protocol. However, if a different protocol is used the neighbour PNC will have to make sure that the neighbouring piconet does not have any transmissions outside the allocated CTA. This to avoid collisions with the parent piconet.

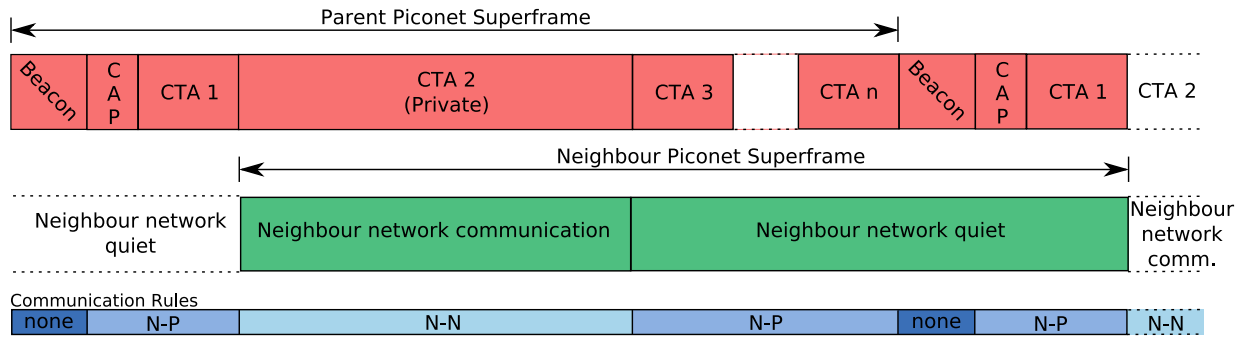


Figure 1-4: The parent piconet and the neighbour piconet superframe relationship. During 'none' there is no peer-to-peer communication. This happens during the beacons. For 'N-P' communication between the parent PNC and the neighbour PNC is allowed. During the 'N-N' period, communication between the various devices associated with the neighbour piconet is allowed.[4]

Table 1-1: Modulation, Coding & Data rates for 2.4 GHz PHY.[4]

Modulation type	Coding	Data Rate
QPSK	8-state TCM	11 Mb/s
DQPSK	none	22 Mb/s
16-QAM	8-state TCM	33 Mb/s
32-QAM	8-state TCM	44 Mb/s
64-QAM	8-state TCM	55 Mb/s

1-1-6 Multiple Data Rates

Like many contemporary communication systems, the 802.15.3 standard supports multiple transmission data rates. In 802.15.3 the beacon, command frames, and the PHY and MAC layer headers are transmitted at the base rate. What is left are the frame payloads, which are transmitted at the best achievable data rate. This is based on the measured signal strength. The measure for this is the receive signal strength indicator (RSSI).[42]

The data rates which can be achieved depend on the modulation scheme used. In Table 1-1 various data rates and modulation schemes for the 2.4 GHz 802.15.3 PHY specification are given.

1-2 mmWave Radio Properties

The physical part of the mmWave WPAN can be broken down in two parts. The first part is the use of electromagnetic waves with a wavelength in orders of millimetres. In Section 1-2-1 reasons for using 60 GHz radio will be discussed. The second part, discussed in Section 1-3-1, is the use of directional antennas.

Table 1-2: Data rate requirements for the HDTV standard for different resolutions, frame rates and number of bits per channel.[34]

Pixels per line	Active lines per picture	Frame rate	# of bits per channel per pixel	Data rate Gbps
1280	720	24	24	0.531
1280	720	30	24	0.664
1440	480	60	24	0.995
1280	720	50	24	1.106
1280	720	60	24	1.327
1920	1080	50	24	2.488
1920	1080	60	24	2.986
1920	1080	60	30	3.732
1920	1080	60	36	4.479
1920	1080	60	42	5.225
1920	1080	90	24	4.479
1920	1080	90	30	5.599

1-2-1 Reasons for Using 60 GHz

Ultra High Data Rate The first reason for using 60 GHz radio is the ultra high data rate which can be achieved. According to the Shannon theory, the data rate is dependent on the bandwidth of the signal. Table 1-2 shows different data rates needed for uncompressed HDTV for different resolutions, frame rates and bits per channel. The data rates offered by the 802.15.3 standard (Table 1-1) are not sufficient for transmission of uncompressed HDTV signals.

For the 60 GHz Milimeter-Wave Radio however this is possible by using a non-complex modulation technique since a total of 7 GHz unlicensed bandwidth is available between 58 and 65 GHz. When four channels are used this leads to a bandwidth of at least 2 GHz per channel. Table 1-3 shows theoretical values of the data rate which can be achieved at certain bandwidths. Modulation techniques with a lower complexity such as On-off Keying (OOK, also called Amplitude Shift Keying or ASK for short) and Binary Phase Shift Keying (BPSK) have a lower data rate compared with more complex modulation techniques as 32-QAM (Quadrature Amplitude Modulation).[9, 22, 43]

Short Distance Another important reason for using Milimeter-Wave Radio for WPANs is the small coverage distance related to millimeter wavelength radio waves, which leads to higher spatial re-use. In free-space the path loss can be written as:

$$L_{fs} = \left(\frac{4r\pi f}{c} \right)^2. \quad (1-1)$$

Table 1-3: Theoretical data rates for the mmWave WPAN, for a given bandwidth B . The roll-off factor is 25% and no coding is used.[25]

Modulation Type	Data Rate (Gbps)	
	$B = 1$ GHz	$B = 2$ GHz
ASK/OOK	0.80	1.60
BPSK	0.80	1.60
QPSK	1.60	3.20
OQPSK	1.60	3.20
8-QAM	2.40	4.80
16-QAM	3.20	6.40
32-QAM	4.00	8.00

Table 1-4: Office material attenuation at 60 GHz and 2.5 GHz.[18]

Material	Loss at 60 GHz	Loss at 2.5 GHz
Drywall	2.4 (dB/cm)	2.1 (dB/cm)
Whiteboard	5.0 (dB/cm)	0.3 (dB/cm)
Glass	11.3 (dB/cm)	20.0 (dB/cm)
Mesh Glass	31.9 (dB/cm)	24.1 (dB/cm)

Where L_{fs} is the free-space loss, r is the range, f stands for the frequency and c is the speed of light in the medium. From this equation it can be concluded that at a large distance using a high frequency leads to a higher attenuation compared with using a lower frequency. This property makes millimetre-wave radio unsuitable for communication over distances large relative to the wavelength. Besides the free-space loss, at 60 GHz radio waves are also absorbed by oxygen. This attenuation can be as much as 12 to 15 dB/km. Most of the time specific material attenuation is higher at frequencies. Compared with 2.5 GHz this may not always be the case or drastic for 60 GHz (Table 1-4).

For large distance communication systems these properties are disadvantageous, however for wireless personal area networks these properties become advantages. The high loss for large distances means that the spatial frequency reuse can be dense if the transmission power is not high. This means that in the same area more independent piconets can be formed when a higher frequency is used. The inter-system interference for 60 GHz communication systems is also lower compared with 2.4 GHz communication systems. Communication over a short range also has the advantage that the propagation delay is lower than communication over a long range which leads to a higher achievable data rate.[18, 22, 35]

Small Antenna Size Another advantage for using millimetre wave radio is the small antenna size. Waves with a high frequency have a small wavelength. Since the physical antenna size is in orders of the wavelength, the antenna will also be small. This makes it

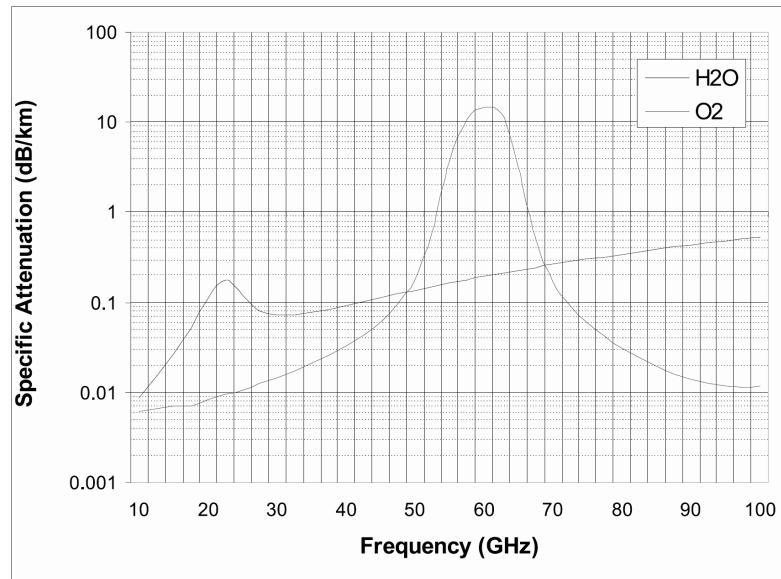


Figure 1-5: Specific atmospheric attenuation between 10 and 100 GHz.[20]

	Frequency (GHz)									
	57	58	59	60	61	62	63	64	65	66
Australia										
Canada and USA	57							64		
Japan			59							66
Europe	57									66

Figure 1-6: Frequency band available around 60 GHz for different areas.[22]

easy to integrate the antenna on chips for devices.

In order to get a high antenna gain without using large horn antennas, array antennas or planar antennas can be used. At lower frequencies the physical size of devices with these antennas would become too large, since multiple antennas should be attached with a pre-determined space between them. With a higher frequency more smaller antennas can be used in the same space, resulting into a higher antenna gain.

Unallocated Band Yet another reason for using 60 GHz is the unallocated frequency band around 60 GHz. As absorption by oxygen occurs at 60 GHz, point to point communication has for a long time seem too expensive at that frequency. Figure 1-5 shows the specific attenuation between 10 and 100 GHz in dB/km. The figure also shows a peak attenuation of more than 10 dB/km. This means that for wireless communication over large distances

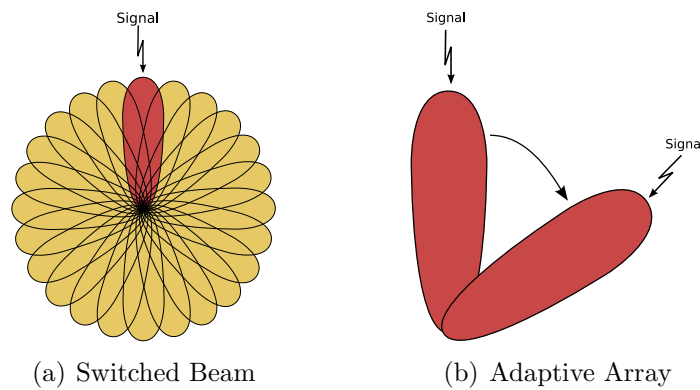


Figure 1-7: Basic principles behind the different types of smart antennas[25]

the attenuation becomes too high, making it unsuitable for long range communication. As can be observed from Figure 1-6 this lead to a large unallocated frequency band between 55 and 65 GHz. Furthermore compared with UWB radio, mmWave radio bandwidth is more continuous and has less restrictions in terms of power limits.[22, 43]

1-2-2 Smart Antennas

Smart antennas are antennas which can focus their radiation pattern towards desired users while at the same time reject unwanted interferes. Smart antennas are not antennas which are smart, but the use of digital processing for the received signals make the total system smart. The use of smart antennas dates back to World War II. The emerge of powerful low cost electronics as well as innovative signal-processing algorithms have made smart antenna systems practical for commercial use.

Smart antennas are composed of antenna elements and a signal processor. The antennas are used to transmit and receive signals. In a three dimensional environment planar arrays of antennas are used. Planar arrays enable the ability to scan the main beam in the elevation and azimuthal direction. The signal processor has two important functions. The first is determining the direction-of-arrival of all impinging signals. Well known algorithms for this are the delay-and sum method, MUSIC (multiple signal classification) and ESPRIT (estimation of signal parameters via rotational invariance technique). The second is setting the appropriate phase and amplitude for the different antenna elements to steer the maximum of the lobe in the direction of the signal of interest.

Smart antennas can be classified into two systems. These are switched beam systems and adaptive array systems.[25]

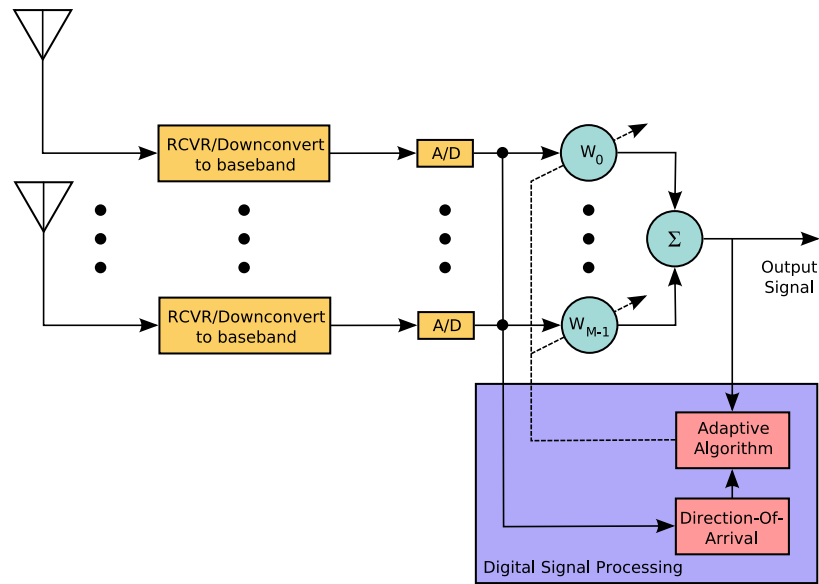


Figure 1-8: Functional block diagram of an adaptive array system with M antennas.[25]

Switched beam systems

A switched beam system uses one of the pre-defined patterns to enhance the received signal. As the transmitter moves, the system chooses which sector provides the best signal strength. The goal of a switched beam system is to choose the sector with the best reception. This does not mean that signal arrives in the angle for which the antenna beam is at it's maximum. In Figure 1-7(a) a switched beam system is illustrated.

Adaptive array

Where switched beam systems choose the best of fixed beams, adaptive arrays have the ability to change the radiation pattern in the direction of the signal. A depiction of this is given in Figure 1-7(b). Besides aiming the maximum of the main lobe in the direction of the signal, switched beam systems also have the ability of suppressing the radiation pattern in the direction of interferers. Adaptive array systems have capabilities for locating and tracking signals. Signals are located using direction-of-arrival algorithms. Tracking is done by changing the amplitudes and phases of the received signals. Because adaptive array systems are more digital-processing intensive, they are also more expensive compared with switched beam systems. A functional block diagram of an adaptive array system is shown in Figure 1-8.

1-3 mmWave Challenges

The challenges associated with the mmWave WPAN are related with the use of directional antennas, the properties of millimeter wave radio and the MAC of the mmWave WPAN.

1-3-1 Directional Antennas

Because of the high path loss at 60 GHz and the transmission power restrictions it becomes necessary to use directional antennas. Directional antennas have a higher antenna gain compared with omnidirectional antennas. This means that for the same transmitted power there will be a higher SNR at the receiver for directional antennas. However the use of directional antennas introduces challenges which do not arise when omnidirectional antennas are used. These problems can be summarised as follows.[17, 39]

Neighbour Location Communication between nodes is only possible when the nodes are within each others reach. For omnidirectional antennas this means that this is only dependent on the distance between the nodes. In case two nodes are too distant the path loss is too high and they cannot communicate. When directional antennas are used in a 3-dimensional environment, besides the distance dependency, communication possibilities also depend on the azimuth and the elevation angles. In order for two nodes with directional antennas to communicate, they need to know each others relative direction, so that the beams can be aimed at each other.

A-symmetrical Links Because of the use of directional antennas the range in which nodes can communicate increases. When nodes switch to omnidirectional patterns, for example to receive a multi-path signal when the direct signal is blocked, it may be that the range between these nodes is too high, and they cannot communicate anymore.

Side Lobe Pattern The radiation pattern of a non-ideal directional antennas contains side-lobes. These side lobes may cause extra interference, which is not known a priori. Besides this, when beamforming is used, the shape of the side lobes vary and are unknown.

Directional Carrier Sensing When the transmitter checks if the channel is free, the transmitter only senses the area which is it able to reach, thus only in a certain direction. Areas of the channel which are not in reach of the transmitter are not checked.

New Hidden Terminal The new hidden terminal problem arises due to asymmetry in the antenna gain and unheard RTS/CTS signals. This for example happens when ‘Node C’ is outside the range of transmitter ‘Node A’, but within the range of receiver ‘Node B’. This is also an implication of directional carrier sensing.

Deafness A node is considered deaf when the node cannot receive a thing from another node due to its antenna gain pattern, while it would receive if the node had an omnidirectional antenna gain pattern. This occurs when the receiving node is beamformed in a direction away from the transmitting node.

1-3-2 High Attenuation by Objects

Another large issues for the mmWave WPAN is the high attenuation of the signal. Because of the low power used for communication in WPANs and the use of 60 GHz objects which would not interfere at 2.4 GHz would now cause shadowing, as shown in Table 1-4. Using directional antennas alone is not sufficient to overcome these problems. This means that the range for communication of the mmWave WPAN is dependent on the network environment. It is more difficult to connect two devices in a room filled with objects, compared with an empty room.

Since the mmWave WPAN is meant to be used in indoor environments humans form an important factor as the signal will also be attenuated by them. Humans form in unpredictable factor in the network because they are not as static as desks or other furniture. The main reason for fluctuation of link quality in the channel will therefore be caused by movement of persons between different nodes. The fluctuations of link quality will have a negative impact on QoS-sensitive applications such as transmission of uncompressed HDTV signals.

1-3-3 802.15.3 MAC

The 802.15.3 MAC is specifically designed for high data rate applications and the TDMA structure in the CTA supports QoS sensitive applications. For the mmWave WPAN however this MAC protocol is not sufficient. The 802.15.3 protocol assumes a full mesh connectivity; all nodes in the network are connected with each other. For the mmWave WPAN it means that a link failure between two devices with the same PNC, either due to humans or an object, results into no possible high data rate connection between the two devices.

1-4 Thesis Goal & Outline

In the recent years it has become possible to transmit data via cables using very high data rates. Speeds which can be achieved are dependent on the technology used. The frequently used USB has a data rate of 480 Mb/s, less common is FireWire with 3.2 Gb/s. To connect HDTV devices with each other HDMI is used which can reach data rates of 10.2 Gb/s. However the use of cables requires an infrastructure at homes. Furthermore the number of devices which can be connected with each other are restricted to the physical connection entries available and cables also have an unaesthetic impact on furniture. Therefore ultra high data rate wireless technologies are desired.

Wireless technologies available at the moment do not offer the data rate needed. For an uncompressed HDTV data rates of 0.5 Gb/s are one of the lowest data rates. For indoor applications Infrared Data Association (IrDA) offers speeds up to 4 Mb/s, Bluetooth is limited at about 1 Mb/s and the 802.11g can offer 54 Mb/s. In order to support high data rate wireless communication the mmWave WPAN should be used.

The mmWave WPAN has some challenges to overcome as mentioned in the previous section. Because of directional antennas, the low transmission power and the short range, the mmWave WPAN is sensitive to objects blocking the channel. Because humans (and animals) move around in a room they are the major cause for random blockage of the wireless channel. The 802.15.3 MAC standard offers a MAC protocol for high data rate WPANs and supports QoS capabilities. However the protocol assumes that all devices in a piconet are able to communicate with each other. In case blocking occurs, the communication will end.

The biggest problem is that the channel between different nodes is often and unpredictably blocked. The goal is to overcome this blocking as quickly as possible. By applying multi-hop routing, explained in more detail further on, this problem can be solved. This means that when two devices are communicating with each other and suffer from blocking, they find a new route to each other using different nodes.

For this thesis the main goal is determining a new route for two communicating nodes which suffer from shadowing between the direct route. First the 802.15.3 protocol is adapted to support resumption of a broken connection. As the time between a broken connection and a fixed connection is important for QoS-sensitive tasks, a mathematical model for the delay will be derived. Finally a simulation will be done by using OPNET Modeler®.

The rest of the thesis is organised as follows: Chapter 2 discusses the possible solutions which can be taken when the direct path between two nodes is blocked. Followed by a proposal of a solution for the mmWave WPAN. Next a mathematical model for the route discovery delay is given in Chapter 3. In Chapter 4 a simulation in OPNET Modeler® is done. The analysis for the mathematical model and the simulation is done in their respective chapters. The last chapter, Chapter 5, conclusions for the thesis will be drawn. Furthermore it contains the comparison between the mathematical model and the simulation, and recommendations for future work are given.

Anti-blocking Proposal

This chapter will describe a solution for reconnecting devices that are blocked in the mmWave WPAN. As explained in the previous chapter the one of the main challenges for the mmWave WPAN is the (temporary) blocking of the channel between two devices. The 802.15.3 standard does not provide a solution to solve this problem. It may happen that a device gets blocked from another device, but cannot resume connection because the devices are not in the same piconet anymore. For this situation inter-piconet routing is needed. This chapter will propose a solution for anti-blocking of devices in the mmWave WPAN. Our proposal uses a multi-hop solution with minimal changes to the 802.15.3 protocol. Our multi-hop solution could easily solve the blocking issue within a piconet. Moreover, we also extend our multi-hop scheme for inter-piconet communications.

The organisation of this chapter is as follows. First possible solutions for anti-blocking will be explained in Section 2-1. The concept of meshed networking and beacon alignment for logical piconets will be explained in Section 2-2. This section is followed by Section 2-3 which discusses changes to the 802.15.3 MAC superframe. The scenarios the proposal is meant to be effective for are discussed in Section 2-4. The proposed solution is worked out in Section 2-5. Finally this chapter ends with a recapitulation of the main points in Section 2-6.

2-1 Possible Solutions

The most likely source for shadowing for the mmWave WPAN will probably be caused by humans. These interruptions have a duration longer than 100 ms and are dependent on the height of the antennas, and the number of humans in the room. The attenuation caused by humans moving through the channel is variable in time and varies between 5 and 20 dB.[13]

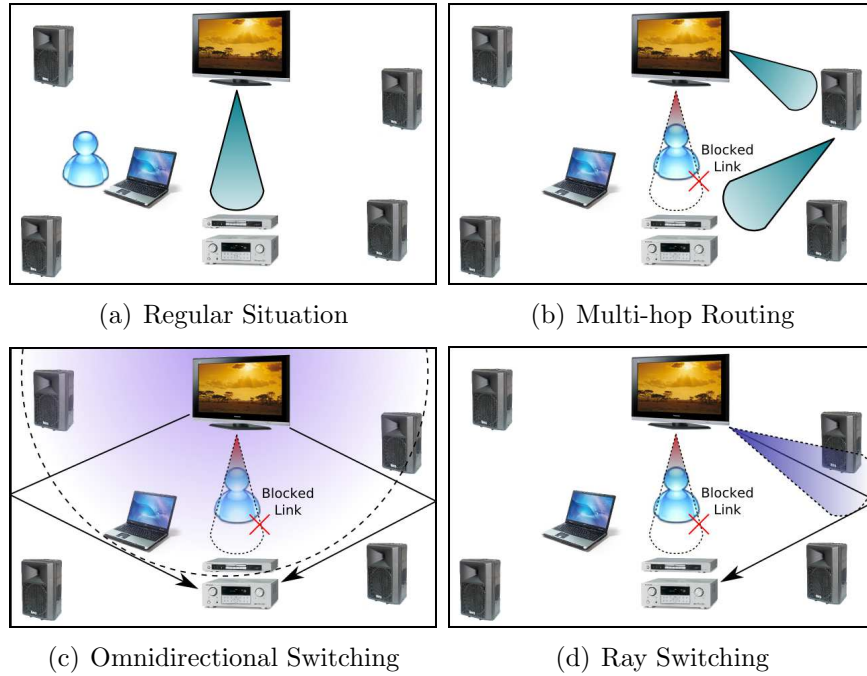


Figure 2-1: The different proposed system solutions. In this example a user passes the direct beam. The television set communicates with the DVD system. There are also speakers across the room which are able to communicate.

In Figure 2-1 three solutions, and the regular situation are depicted. The solutions can be summarised as follows.

1. *Multi-hop Routing*: for this solution the data is not directly send from one node to the blocked node In stead an intermediate node, which can connect to the blocked node directly, is used. For multi-hop routing the most promising path from the sender to the receiver is chosen.
2. *Omni Switching (Multi-rate supported)*: when signals are transmitted, there are always multi-path components present. Switching from directional to omnidirectional, causes a drop in strength of the direct component, but stronger multi-path components.
3. *Ray Switching (Multi-beam supported)*: when the line-of-sight is blocked, it might be possible to communicate using a different ray. In this mode the antennas use non-line-of-sight communication.

All these solutions need a checking algorithm, so when a person blocks the direct signal the system has to switch to the desired solution as quick as possible. When the person is not blocking the signal anymore, the system has to switch to the previous mode again. Thus the solutions require continuous monitoring of the link, or it should always select the

best solution. This mechanism should operate at the physical layer. Another assumption which can be made is that the data which is transmitted, is sent in the Channel Time Allocation Period, since the data will have QoS restraints.

2-1-1 Multi-hop Routing

In Figure 2-2 multi-hop routing is depicted. When the direct path is blocked, a new path to the destination node is searched. First a new route to the node needs to be discovered. After that the new route should be able to guarantee as much bandwidth needed as possible. When the direct path is available again, communication should again go according to the direct path. Both [26] as [5] claim that the use of directional antennas in a multi-hop network have a higher throughput than the use of omnidirectional antennas. This means that the antennas should remain in a directional mode.

Forwarding of the data should be done at the network layer. Here also QoS agreements are made. So when a connection is going to fail or the link quality gets low, a route rediscovery algorithm has to be initiated, after that the route which can provide the QoS requirements as good as possible will be chosen.

This approach has various consequences. An obvious result of the multi-hop approach is a larger delay. The delay is initially caused by the route rediscovery, and later by communication via an intermediate node. As the antennas stay directive, the intermediate node has to switch from communication with the transmitter to communicating with the receiver. This means that for high data rate applications, the total data rate will at least be halved. Another consequence is that the transmission routing protocol has to be changed, so that the update of topology information is included.

Route Discovery Process

Multi-hop routing can be done either proactively or reactively. A proactive solution, also called table driven, uses a routing table, or network information is given a priori. Each node in the network is required to have a routing table. Changes in the network topology are propagated to all the nodes in order to maintain a consistent network view. Well known proactive routing algorithms are DSDV, WRP, and OLSR.

For a reactive solution, or on-demand routing, route discovery is initiated when no route can be found to the destination. The routes are only created on demand by the source node. The route discovery process ends when a route has been found or all possible permutations have been examined. Once a route has been found, it is maintained by a route maintenance procedure until it is no longer required or when the destination becomes inaccessible. Examples of reactive protocols are AODV, DSR and TORA.

Besides proactive and reactive routing also hybrid routing can be considered. Hybrid routing combines proactive and reactive routing. For example for communication for nodes

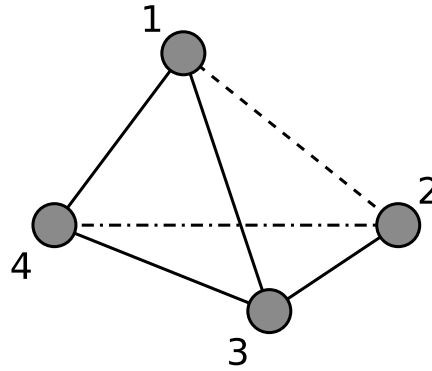


Figure 2-2: A small network where the solid lines are good links, the dashed line represents a blocked link and the dot-dashed line corresponds to a weak link. For the multi-hop solution, node 1 communicates to node 2 via node 3 or 4, depending on quality the nodes can offer. Since the link between node 4 and node 2 is weak, the quality of the connection is lower. So the eventual data transfer will be from node 1 to node 2 via node 3.

that are near proactive routing is used and for nodes who are distant reactive routing is used, or the other way around. Since the WPAN is considered to be a small network, hybrid routing will not be considered. [31, 37]

In [8] it is concluded that for a semi-static small ad hoc network proactive routing is a better solution than reactive routing. Proactive routing results in a better response time, less overhead in a small network and a higher success of packet delivery. This means that QoS requirements can be achieved better. The downside of proactive routing is that a routing table has to be maintained. For fast changing networks this means that when a packet is sent, the routing table already may be outdated. This also means that extra signalling is necessary to check the neighbours and update the routing tables. This extra signalling uses both bandwidth as well as battery resources. Nodes in a sleep mode are also required to wake up in order to receive the topology updates.[31]

When a choice has to be made for either proactive or reactive routing, it is important to keep the application in mind. For now, the application for the mmWave WPAN will be the replacement of cables for high data rate services. Examples of this is transmitting a HDTV signal from a video recorder to the TV, or a video signal from a handheld camera to a PC. These networks will be small (less than 16 nodes), have low mobility, and power will not be considered a bottleneck. Another important aspect of these networks is that movement of humans will be the most likely source for blocking of the channel. This causes the channel and the network to change fast. Since reactive routing performs quicker than proactive routing for fast changing networks, a reactive solutions would perform better.[13, 23]

2-1-2 Omni-Switching

The antenna that will be used for the mmWave WPAN will not be an antenna which transmits all its power in a single narrow beam. This means that some of the power won't

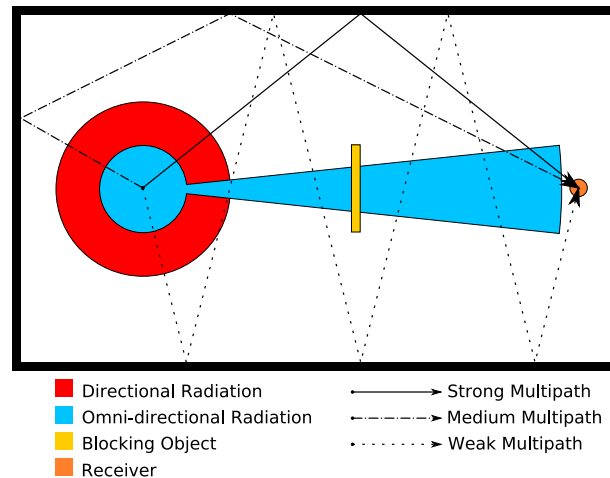


Figure 2-3: A schematic view of the radiation pattern of a directional antenna with a narrow beam (in blue) and the radiation pattern of an omnidirectional antenna (in red). Although the power in the direct path is higher for the directional antenna, in case of blocking the power of the multi-paths are stronger in the omnidirectional case.

be blocked by the interfering person and will be able to reach the receiver. Compared with directional antennas in this case it would be better to switch to omnidirectional antennas. When a directional antenna with a half power bandwidth of for example 10° is used, and the person blocks this 10° beam, half the power is over to reach the receiver. However when an omnidirectional antenna is used, and the person again blocks 10° , a little more than 97% of the power will not be blocked by this person. In Figure 2-3 a simplification of a radiation pattern of a directional antenna is shown against an omnidirectional pattern.

Switching from directional to omnidirectional antennas has two important implications. First at the physical layer, the lower antenna gain may cause nodes that could communicate in the directional mode to be invisible for each other in the omnidirectional mode if the data rate remains the same. The nodes can still communicate, but then the data rate has to drop. Another important implication of a lower gain is a lower signal-to-noise ratio (SNR), and thus a higher bit-error-rate (BER). Additionally at the MAC layer, a node which would not interfere with the receiving node, could now cause interference. So a Hidden-Terminal problem is added. Because of the change in the exclusive region, where two separate connections were possible, it might now result in just one possible connection.

For the channel the switch from directional to omnidirectional antennas also means that the RMS delay spread becomes larger. Implying that the received signal will be spread out more over time. For directional antennas the RMS delay spread is about 2 nanoseconds, where as for omnidirectional antennas it is about 20 nanoseconds.[18, 27, 21] This means that the total system becomes slower, what may have an impact on the achievable data rate.

Besides the larger RMS delay spread, the data rate for omnidirectional communication is also lower. Compared with directional antennas, omnidirectional antennas have a lower

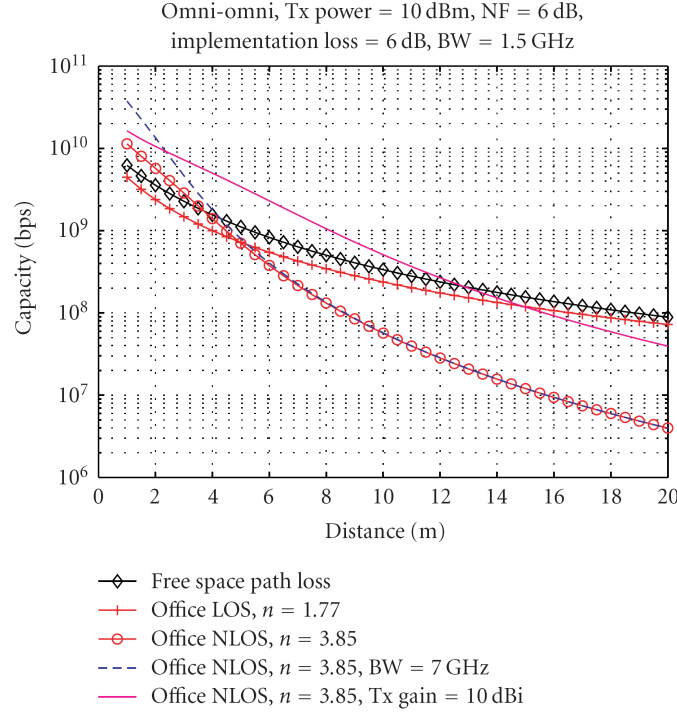


Figure 2-4: The capacity of the channel under different conditions set against the distance. From this Figure it can be observed that using directional antennas (pink solid line) results in a higher channel capacity compared with omnidirectional antennas (red solid line with circular markers). This effect becomes more apparent as the distance between the receiver and transmitter increases.[43]

gain. The power transfer function of a free-space channel can be given by:

$$\frac{P_{Rx}}{P_{Tx}} = G_{AT} L_{fs} G_{AR} \quad (2-1)$$

Here P_{Rx} and P_{Tx} are the received power and transmitted power respectively. G_{AT} is the gain of the transmitting antenna and G_{AR} is the gain of the receiving antenna. L_{fs} is the free-space loss as defined in Equation 1-1. This means that the received power will decrease, causing a lower signal-to-noise ratio (SNR). According to Shannon's channel capacity theorem, the capacity which is given as $C = B \log_2 \left(1 + \frac{S}{N}\right)$ will also decrease, resulting in a lower data rate. Figure 2-4 shows the relation between the distance and the capacity of the channel. It also shows the capacity for different propagation parameters and different antenna gains.[25, 43]

In order to make omni-switching work, changes have to be made to the receiver. Also changes in the MAC protocol should be made. The receiver should be designed in such a way that weaker but more multi-path signals can be received correctly and reconstructed into the original signal. The MAC protocol should be arranged in such a way that the when devices start to interfere with each other due to the switch to omnidirectional antennas,

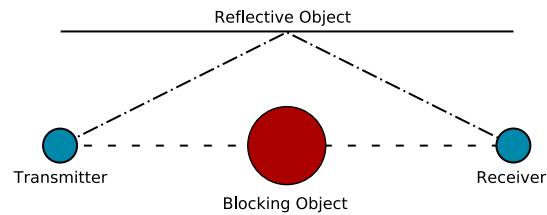


Figure 2-5: The dashed line represents the direct link between the communicating nodes and the dot-dashed line the link via a different ray, in this case a reflection by a reflective object.

the frames also have to be shared. This will result in less frames for communication. The available frames communicating nodes get should not only depend on the bandwidth needed, but also on the type of application. Time sensitive applications should get a higher priority over other applications. for example a HDTV signal from the recorder to the TV should get a higher priority over a data signal for transmitting a movie from a handheld camcorder to a PC.

2-1-3 Ray-Switching

In Figure 2-5, the ray switching solution is shown. When the direct path is blocked, the communication is proceeded via a more or less reflective object.[33] To simplify the problem, an empty room with concrete walls is considered. The only object that will cause blocking is the person. Although concrete walls are difficult to penetrate, they are not perfect reflectors. The reflection coefficient of a concrete wall of 3 cm is about 0.43, which means a loss of about 7 dB.[21] Besides this loss, losses due to a longer path also have to be considered. This solution can be seen as re-establishment of the connection over a weaker channel. The angles of the antennas can be changed by using a scanning mechanism. So disconnected devices start a rediscovery process by transmitting a signal over every angle and fixing their beam to the angle which receives the highest power.

When two nodes are communicating over a large distance (10 meters), switching to a reflected signal will raise the SNR, perhaps even beyond the level of the ability to receive it well. Also just like with omni-switching, the new path for communication may interfere with nodes, which did not know of the existence of the other communicating nodes.

Ray Switching requires a change in the MAC layer so nodes switching angles will not interfere with other nodes which are already communicating. Also when the power is low and the data received should match the data transmitted, switching to a mode with stronger error correction should be possible. Switching to another angle is done at the physical layer using beamforming. A switching mechanism has to be implemented to detect a reconnection between the nodes.

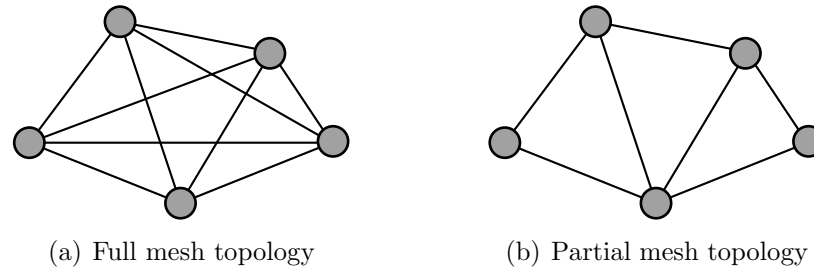


Figure 2-6: Mesh network topologies.

2-1-4 Evaluation

The largest disadvantage for using omni-switching is the lowered data rate. mmWave WPANs are used specifically for the ultra high data rate achievable. Lowering the data rate is a deficiency of the 60 GHz radio capabilities.

The ray-switching solution works fine if a node is mobile. However for the mmWave WPAN the main reason for blocking is mobility of humans. Changing the direct ray ray leads to a increase in the distance of the transmission. Furthermore, absorbtion of walls and other objects may cause too much attenuation.

The multi-hop solution seems more promising. Using intermediate nodes, a very high data rate can still be used for communication. This solution does however require nodes which are capable of forwarding the traffic. Since the mmWave WPAN will be used in future home networks, the number of devices capable of forwarding data should not be considered a major issue.

2-2 Wireless Mesh Personal Area Networks

In mesh networking there are two connection arrangements: *full mesh* topology & *partial mesh* topology. In a full mesh topology all the nodes are connected directly to each other. Whereas in a partial mesh topology some node may be connected to all the nodes and some of the other nodes are only connected to the nodes which exchange most data. In Figure 2-6 the two types of mesh topologies are shown.[1, 15]

The 802.15.3 assumes a piconet has a full mesh topology. All the devices should be connected with each other in order to communicate with each other. Recently the 802.15.5 group has been formed. This group is chartered to determine necessary mechanisms at the MAC and PHY layer to enable mesh networking for WPANs[1]. Networks with disconnected devices have more a partial mesh topology in stead of a full mesh topology.

In [16] a proposal for meshed networking for 802.15.5 is made using the 802.15.3 specifications. In stead of one piconet, logical piconets are used. A logical piconet is a group of devices containing associated PNCs. A logical piconet may contain multiple associated

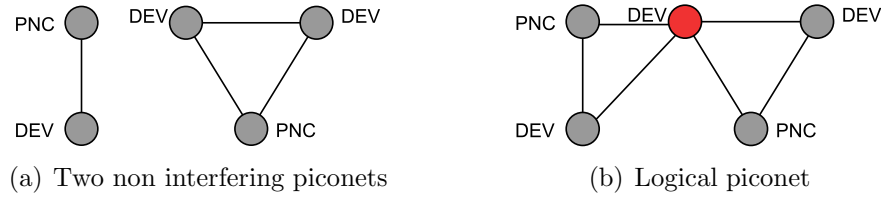


Figure 2-7: Two non interfering piconet in (2-7(a)). In (2-7(b)) the red device represents a device connected with two PNCs. If interference free coexistence is possible, the network is a logical piconet.

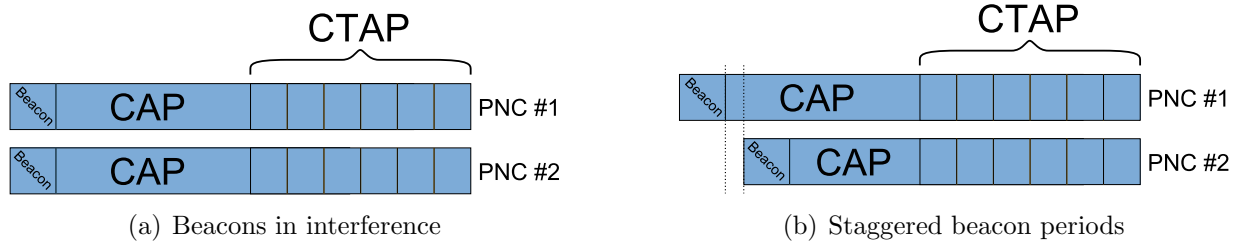


Figure 2-8: An example of two superframes where the beacons interfere with each other (2-8(a)). By staggering the beacon periods (2-8(b)), the beacons do not interfere with each other.

PNCs. The PNCs align their transmissions in such a way that there is interference free coexistence.

2-2-1 Logical Piconet Approach

As described in [16], a logical piconet is a grouping of piconets that support non-interfering coexisting. Figure 2-7(a) shows two piconets which do not interfere with each other. Because of the non interference, the beacons can be transmitted at the same time, as shown in Figure 2-8(a). With the topology given in Figure 2-7(b) the beacons would interfere with each other. By aligning the beacons as shown in Figure 2-8(b), interference between the beacons is avoided. Two non interfering piconets can have their beacon period at the same time, resulting into an optimal use of the CAP. In the logical piconet devices retransmit information gathered from beacons transmitted by PNCs. These messages are called heartbeats. The PNCs use these heartbeats to align their beacons.

Comparison with Child Piconet

In Section 1-1-5 of Chapter 1, child piconets are explained. A child piconet is a dependent piconet, which can be used to extend the range of a network. Communication within the child piconet is done at a time allocated by the parent piconet controller.

Using a logical piconet containing aligned non interfering piconets offers the same functionality of a piconet containing child piconets. For every piconet there is a beacon, a CAP and the CTAP. Instead of having a parent piconet, a logical piconet uses a senior PNC where the other PNCs have to align to.

The biggest difference between the logical piconet and a child piconet configuration is sharing of the CAP. Every single child piconet has it's own CAP. With a large network, containing many child piconets, the overhead of the CAP causes a lower efficiency. Because the CAP of a child piconet is within an allocated time frame, all other devices, which are not included in the child piconet should be silent.

For the logical piconet this is not the case. During the CAP all nodes are able to communicate. Because CSMA/CA scheme of the CAP, collisions of messages of different piconets will be avoided. Also unlike the case with child piconets, beacons can be transmitted at the same time, provided that they do not interfere with each other.

All with all using logical piconets the channel is more efficiently used compared with child piconets. For a small number of piconets this efficiency is not noticeable. However as the number of piconets increases, the efficiency will also increase.

2-3 Modification to the 802.15.3 MAC

The mmWave WPAN has the possibility for multi-rate communication, and uses array antennas. When the superframe of the 802.15.3 MAC is used, these two factors make it possible to transmit the beacon and the CAP in a omnidirectional manner. This has the advantage that every node in the WPAN will receive messages transmitted during these periods. Also the main advantage of the directional antennas is that it makes it possible to communicate at an ultra high data rate. This ultra high data rate will be needed more for the channel time allocation period, where most of the data between devices is transmitted, instead of the beacon or contention access period, where control information is transmitted. In Figure 2-9 the MAC superframe is shown, with different colours indicating different transmission modes. MCTAs are used for management between the piconet controller and devices. Since these messages are short, and more than one device can communicate with the piconet controller, the directional broadcasting mode is used.

By using this scheme for transmission, many of the challenges caused by the use of directional antennas as discussed in Section 1-3-1 are solved. *A-symmetrical links* are not a problem because connection is set up by listening to the beacon and using the CAP, which are in the omnidirectional mode. Because of the TDMA structure of the CTAP and only one concurrent transmission is allowed, the *side lobe pattern*, *directional carrier sensing*, the *new hidden terminal* problems are not considered. *Deafness* and *neighbour locations* can be solved by letting the master know when a device has to communicate with another one, and by implementing a neighbour discovery algorithm during the CAP. By using neighbour discovery, devices should be able to know relative direction to other

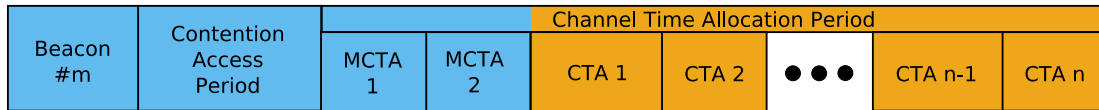


Figure 2-9: The superframe format for the mmWave WPAN. It has the same structure as the piconet superframe given in Figure 1-2. The difference is that the datarate and transmission mode is not constant during the whole superframe. In the blue period a low datarate and an omnidirectional mode are used; in the yellow period a high data rate and a directional mode is used.

devices. When a peer-to-peer connection is set-up, the devices can look the DEVID in a table and aim their antenna in the required direction.

Since the actual transmission in assigned CTAs happens on a peer-to-peer basis, it is essential for the nodes to know each others relative direction. The direction of arrival of a signal can be estimated by using signal processing techniques. During the beacon and CAP, nodes which do not need to communicate can listen to the channel, and estimate the direction of nodes who are transmitting. Since every node has a distinct DEVID, the different directions belonging to a device can be stored in a table.

2-4 Scenarios

The proposals for blockage of communication will be tested using two scenarios. When looked upon a single piconet there are two different situations possible when the link between two devices is blocked. Figure 2-10 shows the regular situation and the two possible scenarios.

- **DEV-DEV failure (Figure 2-10(b)).** The first situation is the blocking of a device to device communication within a piconet. Both devices are still able to hear the piconet controller, and can thus receive transmission schedules from the piconet. This means that there is at least one common neighbour. It is also possible that the two nodes have more than one common neighbour.
- **PNC-DEV failure (Figure 2-10(c))** The second situation is blockage of communication between two devices, where one of the devices is not able receive data from the piconet controller. As stated before in Section 1-1-4 devices which do not receive the beacon from the PNC will disassociate themselves from the piconet. This situation is not limited to loss of communication between two devices, it can also be a device and the piconet controller. Another aspect is that it is more problematic than a device to device link failure within the same piconet, since unassociated devices are not able transfer data to other devices.

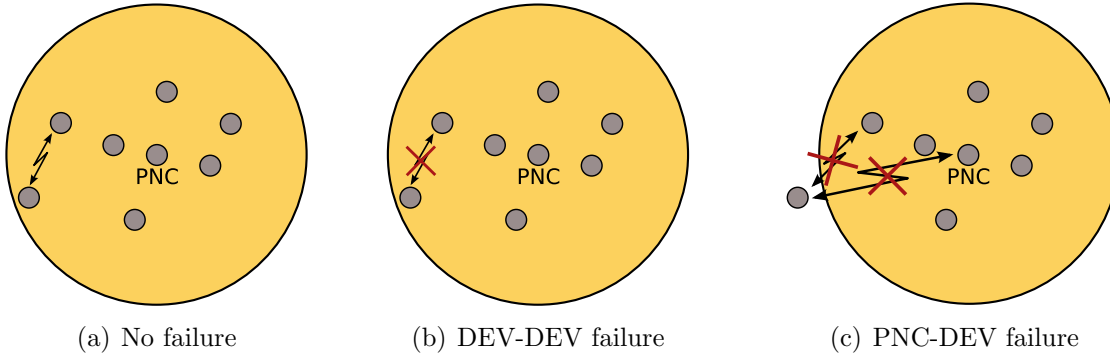


Figure 2-10: The regular situation (2-10(a)) and the two other scenarios. (2-10(b)) shows communication failure between two devices in the same piconet, (2-10(c)) shows communication failure between devices where one of the devices does not receive any data from the piconet controller.

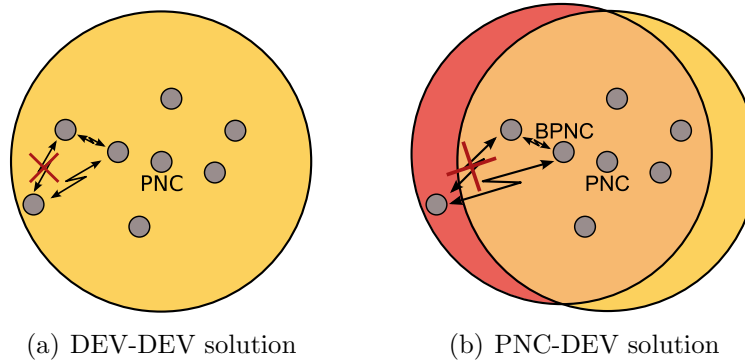


Figure 2-11: Solutions for failure with a common piconet controller (2-11(a)) and failure where one device is excluded from the piconet (2-11(b)). The PNC is the Piconet Controller, the BPNC the bridging Piconet Controller. The bridging PNC is the Child Piconet Controller for Proposal #1 and a Piconet Controller for Proposal #2.

2-5 Proposed Solution

In short the proposal does the following. In case blocking occurs the devices initiate a route discovery process to reconnect with each other. When the disconnected devices are in the same piconet the devices will use another device, which is able to communicate with both devices, as a bridge to communicate. Should it happen that one of the disconnected devices gets excluded from the piconet, another piconet is formed containing the source device and the destination device. Inside this piconet an intermediate device is used to forward the traffic. Both of these situations are illustrated in Figure 2-11.

The proposal for overcoming blockage in the mmWave WPAN can be divided in the following parts.

1. **Determine link failure:** Here it is determined when peer-to-peer communication between devices is lost.
2. **Route discovery:** Finding a new route to the disconnected device.
3. **Resume connection:** Transfer data from the source device to the destination device using intermediate devices.
4. **Determine link re-establishment:** When peer-to-peer communication is possible, switching back induces less overhead.

Next all these parts will be explained using the scenarios described earlier.

2-5-1 Determine Link Failure

The moment of switching is crucial in order to continue the interrupted communication. There are two ways to detect communication loss. First there is not receiving acknowledgements anymore, and then there is detecting a drop in the received signal power.

Missing acknowledgements

During the CAP and CTAP, acknowledgements are used to verify if data has correctly been received. The data of transmissions is divided in frames. In 802.15.3 there are three acknowledgement schemes. Figure shows the Immediate Ack (Imm-Ack) scheme, where every frame is acknowledged after an Short Inter Frame Spacing (SIFS) period. Besides this scheme, there is also the No Acknowledgement (No-Ack) scheme and the Delayed Acknowledgement (Dly-Ack) scheme. As the name suggest there are no acknowledgements transmitted for the No-Ack scheme. This for data which does not need to be acknowledged or the acknowledgements are done at a higher layer. For the Dly-Ack, the not every data frame is acknowledged individually; all data frames are acknowledged at the end of the transmission.[4, 41]

In case two nodes are communicating and there are no acknowledgement received by the transmitting node, the transmitter assumes that the receiver did not receive the data. In most cases the transmitter will retransmit the data until an acknowledgement is received. After a certain amount of retransmissions, the transmitter will assume that the receiver is not within reach and the communication will end. Compared with wired networks error rates on wireless links are orders of magnitude higher. Packet losses are common and cannot always be compensated by Automatic Repeat Request (ARQ) or Forward Error Correction (FEC). Therefore loss of a single packet cannot be considered loss of communication between two nodes. Thus more packets should be lost in order to determine that the channel is blocked.[32]

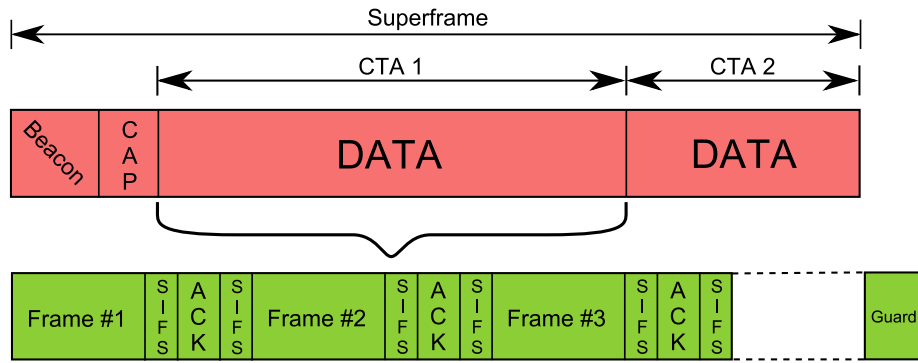


Figure 2-12: Immediate Acknowledgements for a CTA. For every frame containing data there is an acknowledgement transmitted after a SIFS period.[41]

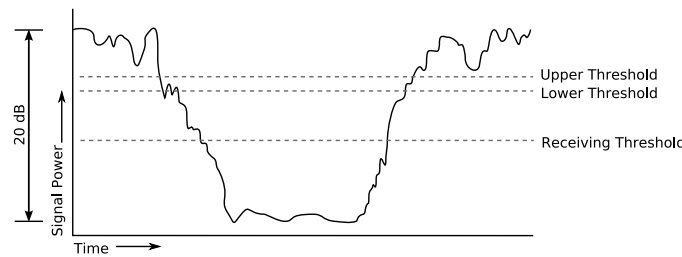


Figure 2-13: Received power over time during blocking. The difference in received power between the shadowed stage and the non-shadowed stage is about 20 dB([14]).

Dropping in signal strength

Another way to see if a channel is blocked is by looking at the Received Signal Strength Indicator, the RSSI. The RSSI is a measurement for the power of received radio signals. When the channel gets blocked the received power does not suddenly drop; rather it drops with a slope.[13] By looking at the RSSI, it can be predicted if the channel is going to be blocked. Since the received power is not constant and fluctuates all the time, setting a threshold value before switching will reduce unnecessary switching. For switching back to the regular way of communicating, there also should be a threshold. Only this value should be higher than the other threshold, else unnecessary switching would also occur. Figure 2-13 shows how the received power changes over time schematically.

2-5-2 Route Discovery

Communication loss within a piconet

When connection loss between two devices has been detected, the following will be done, During the CAP the devices will initiate a discovery process using directional antennas to broadcast route request packets. Other devices which receive this message will forward the

discovery message containing information about the previous hops and the minimal power which is received. The minimal received power will be an indication of the maximum data rate which can be achieved using multiple hops.

In case the route request packets reach their destination, the destination node will reply over the route which has the best data rate possible. When the acknowledgements reach the source, the route will be reserved for communication in the CTAP.

If no route can be found from the source to the destination, a device not found message will be transmitted to the source. Only when the source sees that the device is still in the beacon of the piconet controller, it will try to re-initiate a route discovery process. If the destination device is not in the beacon and no other devices are able to find it, the source will terminate the connection.

Changes in the transmission angle, for example caused by moving devices, will cause a direct reply from the destination device to the route request message. Using this message the source device can determine the new direction to the destination device. When this is done it is possible to resume peer-to-peer communication.

Communication loss outside a piconet

In case peer-to-peer communication loss occurs and one of the devices is out of reach of the piconet controller, a different kind of solution is necessary. When the channel between a piconet controller and a device is blocked, the device will become disconnected from the piconet. The disconnected device will listen the channel continuously and will try to reconnect to a piconet. A device which cannot receive beacons is only allowed to transmit an immediate acknowledgement to data intended for that device. This means that the device which is still in the piconet has to initiate the route discovery process. Other devices will forward this message. When the destination device receives this message, it will be able to respond. The intermediate device will see that this reply is of an unassociated device and will try to form another piconet, aligned with the senior PNC.

The source device as well as the destination device should join the newly formed piconet. When both devices have joined the piconet they still cannot communicate directly. However, since both devices are now in the same piconet and both are connected to the same piconet controller, the problem becomes a communication loss within a piconet. The solution described in the previous subsection will then be used to allow the devices to communicate with each other again.

2-5-3 Resume Connection

When the new route has been established between the source device and the destination device, MAC frame forwarding should be applied in order to have as less overhead as possible. When CTA reservation is successful, all the devices reserved in that CTA are

able to communicate sequentially. So the devices listen in the direction they expect to receive a frame or acknowledgement from. When nothing is heard, the device will not communicate. In Figure 2-14 the superframes and frames belonging to a CTA are depicted.

Since the new route contains more than one hop, the acknowledgements time-out has to become larger. Only when the frames reach the destination, acknowledgements will be transmitted. After the acknowledgement time-out of the transmitter has passed, the frame will be retransmitted. After three retries a new route discovery process will be initialised.

2-5-4 Determine Link Re-establishment

Using multiple hops to communicate is not as efficient as using a single hop for communication. Since every frame has to be transmitted and acknowledged at least twice, the throughput of the CTA diminishes. Therefore the multi-hop solution should be reverted in case the channel is not blocked anymore. This means returning to the situation depicted in Figure 2-10(a).

Communication loss within a piconet

In case communication between two devices is ended, the following can be done to check if it is possible again to re-establish the original piconet. Since every device needs to transmit a message to the PNC in order to stay associated with a piconet, the devices will transmit a message to the PNC in an omnidirectional mode during the CAP. Other devices can hear this message and the disconnected nodes can try to overhear each other messages to the PNC. When the devices can hear each other, the (new) direction can be calculated, and the directional connection can be resumed.

Communication loss outside a piconet

In case communication between a piconet controller and a device has ended, another piconet will be formed. Since the senior piconet controller transmits a beacon in every superframe, the disconnected device can listen to the beacon. There will be no communication between other nodes during the beacon of the senior piconet controller, as shown in Figure 2-14(b). When the disconnected device can hear the beacon again it can join the initial piconet. After joining the initial piconet, the source and destination devices can use the piconet and start a route discovery process to find each other. The newly created piconet should not be terminated immediately. In case blocking occurs again, the devices can use that piconet quickly to resume communication.

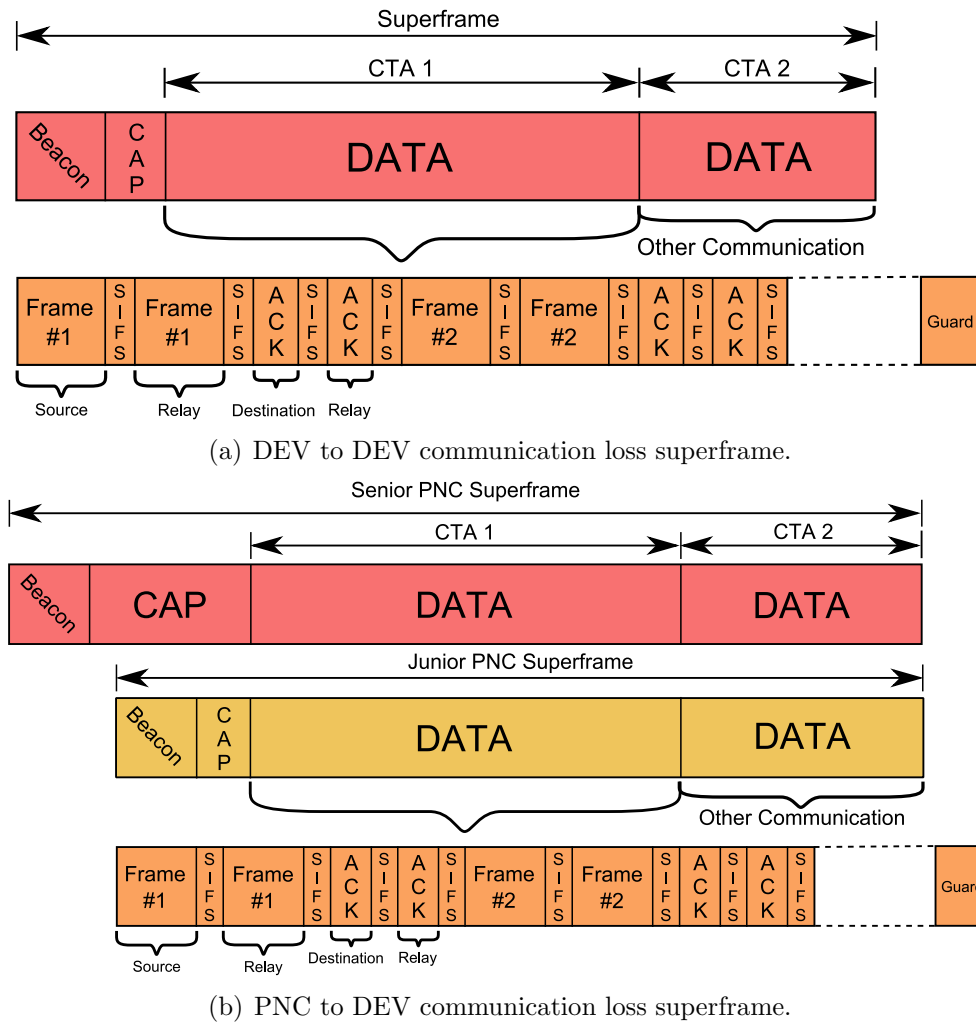


Figure 2-14: The superframes for the solutions of the different scenarios. The superframe for a device to device communication loss within the same piconet (2-14(a)) and one device excluded from the piconet 2-14(b). In this example the devices who lost each other are communicating during CTA1. During CTA2 other devices are communicating.

2-6 Conclusions

- This chapter started with the explanation of different possible solutions for two blocked devices to resume connection. These solutions are:
 - Multi-hop Routing: Using intermediate nodes to forward messages.
 - Omnidirectional Switching: Switching to an omni-directional antenna, and using multi-paths to receive the messages.
 - Ray Switching: Changing the direction of transmission and the direction of reception to a secondary weaker path.
- The 802.15.5 group is specified to enable mesh routing for WPANs. Using logical piconets with aligned non interfering 802.15.3 MAC schemes, mesh routing is possible using piconets. Child piconets can be formed in order to extend a piconet. However by enabling logical piconets the channel can be used more efficiently.
- Using broadcasting during the Beacon and CAP, and directional transmissions during the CTAP, makes the 802.15.3 superframe suitable for directional antennas. This means that the mmWave WPAN can use directional antennas as well as the 802.15.3 MAC.
- Our proposed solution to resume connection after a connection failure has the following features:
 1. A link failure between two devices can either be detected using an acknowledgement scheme, or by looking at the RSSI.
 2. Using a route discovery method, the route between the source and the destination can be found using at least one intermediate node.
 3. If the source and the destination device share the same piconet, an intermediate device is used to forward the data. In case the source or the destination are separated, a new piconet, containing both devices, has to be formed. This new piconet has to be aligned with the old piconet to avoid interference. After the new piconet has been formed an intermediate device is used to forward data between the source and the destination device.
 4. Using intermediate devices degrades the throughput as every data frame is transmitted twice. In case the source and destination device can hear each other again, they should try to resume their connection on a peer to peer basis.

Mathematical Analysis

In the previous chapter a solution to the blocking problem is proposed. An important aspect of the solution is route discovery. To give an indication of the performance of the route discovery process, the delay for this process is used as a metric for evaluation. A disconnection between two nodes will not be noticeable to the user if the nodes can re-establish a connection fast. This chapter will give a mathematical model for the delay for such a route discovery process. Two mathematical models using CSMA/CA under different traffic conditions and network topology will be discussed. The route discovery message consists of a Route Request (RREQ) process and a Route Reply (RREP) process. The RREQ messages are directionally transmitted in all the possible directions. Since the destination device knows who it received the RREQ message from, the RREP message can be unicasted.

First a simplified model will be explained in Section 3-1. This model is valid for a one-dimensional network. This means that all the nodes are placed in a line. For this model the only traffic that will be considered in the network is induced by the route discovery process. Next, in Section 3-2 an extended model which assumes saturated traffic will be examined. For this model all nodes have data from the application layer to transmit. The simplified model forms a lower bound for the time needed for route discovery. The extended model forms the upper bound for the time needed for route discovery. This chapter ends with a conclusion in Section 3-3. The relation between the simplified model and the the model for saturated traffic will be discussed in this section. The validation of the mathematical models from this chapter with the simulations of Chapter 4 will be done in Chapter 5.

3-1 Simplified Model

First a simplified, one-dimensional, mathematical model will be formed. The MAC protocol used as backbone for the mathematical model is CSMA/CA. The simplified model does



Figure 3-1: Straight Line Topology & Non Straight Line Topology. For the straight line topology messages from Node 1 to Node 5 will subsequently propagate through the network. For the non straight line topology messages from Node 2 might collide with messages from Node 3 when both of them are transmitting to Node 4.

not assume that other traffic is going on. The RREQ messages of different nodes are also considered to be received correctly and no collision occurs. This model is only valid in case different RREQ and RREP messages do not collide with each other. The only case when this will happen is when the nodes are placed in a line and only the neighbours of a random chosen node don't have neighbours in common. This means that this model is only valid for one-dimensional networks, where the only traffic is generated by the route discovery process. Figure 3-1 explains why the straight line topology is necessary for directional antennas graphically.

3-1-1 Analytical Model

The expected RTT is described as the expected time needed for RREQ added with the expected time needed for RREP. These two in their turn depend of other parameters like the number of hops to be taken and the back-off window size. Equation 3-1 gives the mathematical model for the expected RTT.

$$\boxed{E[RTT] = E[D_{RREQ}] + E[D_{RREP}]} \quad (3-1)$$

Every individual transmission of packets has to wait a random number of slots before transmitting, and has to wait at least for the duration of SIFS, T_{sifs} , before a packet can be transmitted. In case there are N_h hops between the source and the destination the average delay for the RREQ ($E[D_{RREQ}]$) is given as:

$$E[D_{RREQ}] = N_h E[N_{tx}] (E[N_{wb}] T_{sl} + T_{sifs} + T_{tx}) \quad (3-2)$$

Here $E[N_{tx}]$ average number of transmissions needed to transmit from the source to the destination for one hop. $E[N_{wb}]$ is the average number of windows the transmission will defer. T_{sl} , T_{sifs} , T_{tx} are the duration of an idle slot, the SIFS and the transmission respectively. RREP messages are not broadcasted, rather they are unicasted. Because the direction of the destination is known, there is only one transmission needed to transmit

from source to destination for one hop. This means that the delay for RREP ($E[D_{RREP}]$) can be mathematically written as

$$E[D_{RREP}] = N_h (E[N_{wb}]T_{sl} + T_{sifs} + T_{tx}) \quad (3-3)$$

The direction of transmission and the average number of windows to defer ($E[N_{wb}]$) are randomly chosen and uniformly distributed. Let N_s be the number of sectors to transmit to and W_0 equals to the maximum number of windows to defer in the first back-off stage. The sectors to transmit to is then given as:

$$E[N_{tx}] = \frac{N_s + 1}{2} \quad (3-4)$$

Where as the average windows to defer is given as:

$$E[N_{wb}] = \frac{W_0 + 1}{2} - 1 \quad (3-5)$$

The number of sectors depends on the antenna beamwidth. In a 2-dimensional environment the next equation is valid for the antenna beamwidth in degrees.

$$N_s = \frac{360^\circ}{B} \quad (3-6)$$

Equating the previous equations gives the total expected RTT for a route discovery process.

$$\boxed{E[RTT] = N_h (E[N_{tx}] + 1) (E[N_{wb}]T_{sl} + T_{sifs} + T_{tx})} \quad (3-7)$$

3-1-2 Results

For the analysis of the mathematical model the input parameters given in Table 3-1 are used. The number of hops and the beamwidth will be varied. Equation 3-7 forms the basis for the mathematical analysis. Figure 3-2 shows the results for the mathematical model given in the previous subsection in a 2-dimensional environment. For this figure, the antenna beamwidth and the number of hops are varied, leading to different RTTs. From this figure it can be said that many hops and a small antenna beamwidth lead to a higher RTT, whereas a small number of hops and a large antenna beamwidth lead to a smaller RTT.

In order to validate the mathematical model with simulations the configuration given in Table 3-1 is used. Furthermore the antenna beamwidth is selected at 60° . The mathematical simulation consists of an increasing number of hops starting with one and ending with five. Each hop simulation consists of 100 000 runs, where an RTT is calculated. Table 3-2 shows the calculated means, standard deviations, maximum and minimum RTTs in milliseconds for the different hop counts. A bar plot of the mean RTTs is given in Figure 3-3

Table 3-1: The the values of different parameters used for the mathematical result. These values are specifically for the mmWave WPAN route discovery.

Parameter	Value
T_{sl} , Duration of BIFS/idle slot	1.2 microseconds
T_{sifs} , Duration of SIFS	0.9 microseconds
T_{tx} , Duration of transmission	0.308 microseconds
W_0 , Back-off windows size	8

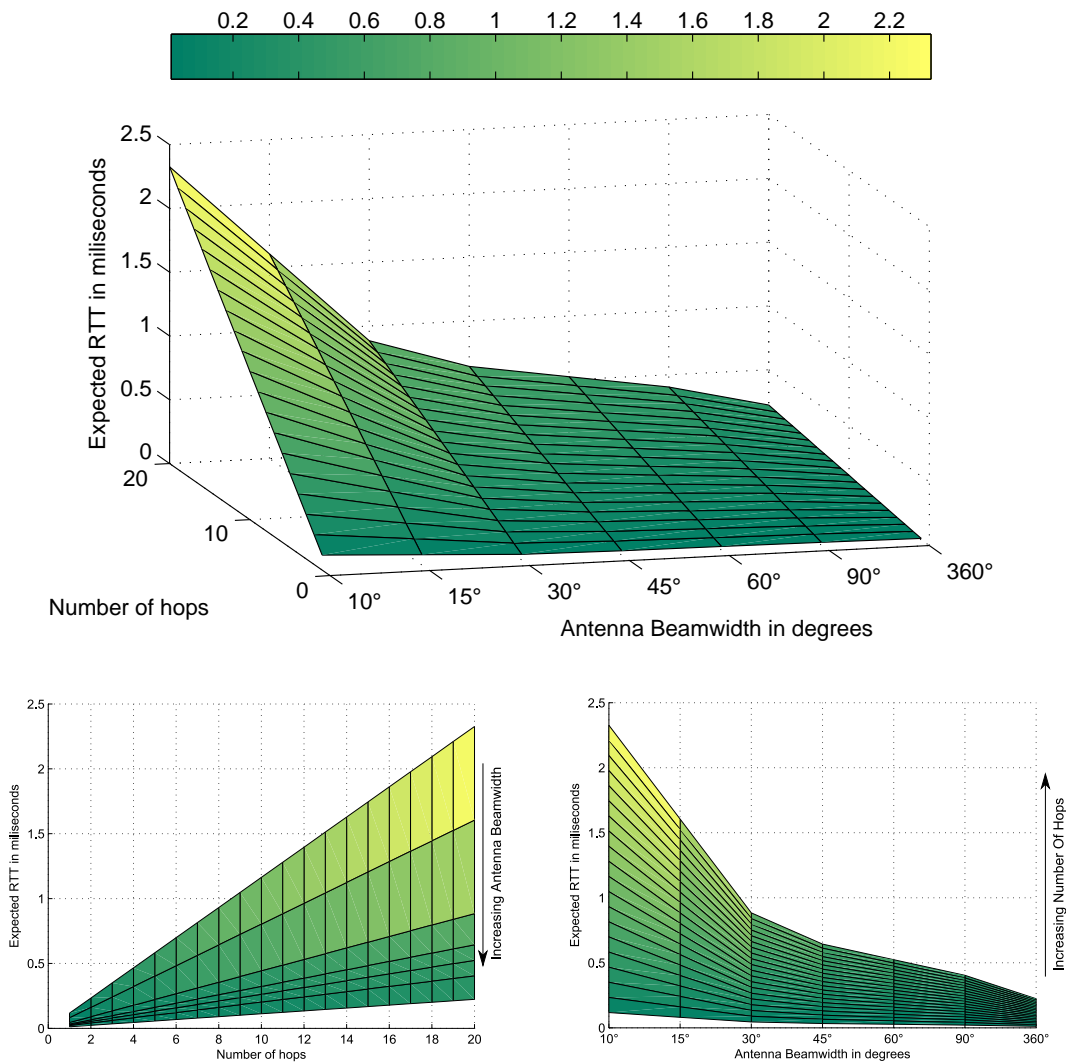


Figure 3-2: Results of the mathematical model

Table 3-2: RTTs calculated from mathematical simulation in milliseconds for different hop counts. Each results consist of 100 000 runs where a RTT is determined. The input parameters of Table 3-1 are used, with an antenna beamwidth of 60° .

Number of Hops	RTT in milliseconds			
	Mean	Std	Max	Min
1 Hop	0.0243	0.0144	0.0673	0.0024
2 Hops	0.0488	0.0204	0.1333	0.0060
3 Hops	0.0730	0.0250	0.1910	0.0133
4 Hops	0.0973	0.0289	0.2426	0.0205
5 Hops	0.1216	0.0322	0.2823	0.0301

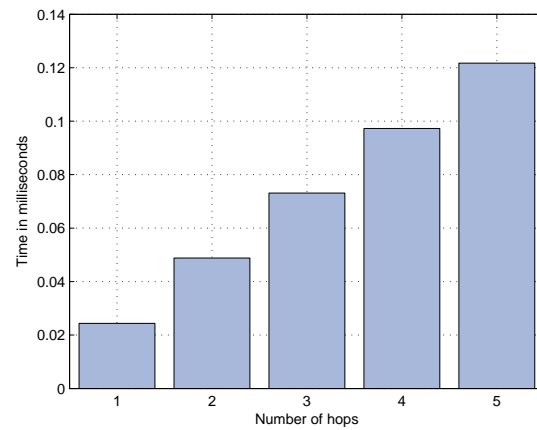


Figure 3-3: Mean RTT for a beamwidth of 60° . The results are from Table 3-2

3-2 Extended model

The simplified model works in case no other traffic is going on. To model a more generic situation this model is insufficient. Because of the CSMA/CA a packet is only transmitted when the channel is sensed to be idle. Where Section 3-1 assumed there was no other traffic going on. The simplified model is also insufficient for the back-off stage. In the previous model there was a random number of back-off stages. During back-off no other traffic was considered. In CSMA/CA the back-off window is paused in case the channel is not idle. To model these two major differences a Markov chain model is used. In [11], [12], [40] and [6] the CSMA/CA mathematical model is discussed. Using the models given in there, a mathematical model for the RTT will be derived.

3-2-1 Analytical Model

The analytical model has the following assumptions. The first assumption is that the network consist of a finite number of n devices. All these devices use the same medium access technique under ideal channel conditions. This means that the channel does not create bit errors and hidden terminals are not considered. This means that all devices in the network can connect with each other and the situation that two devices which cannot see each other transmit to the same destination is not included in the model. Furthermore every device has data from the application layer to transmit, thus saturation conditions are considered. The nodes are all in steady state resulting into a constant probability of collision p over time.[12]

Backoff Procedure

Based on [6, 12], a Markov Chain Model is devised. Figure 3-4 shows the Markov Chain Model used to model the back-off procedure of CSMA/CA. $b(t)$ is the stochastic process which represents the size of the back-off window for a given station at time instance t . $s(t)$ represents the back-off stage $[0, \dots, m]$ of the station at time t , where m represents the maximum retransmissions. When there are $m+1$ collisions the packet is dropped. Combining these two processes gives a two-dimensional process $\{s(t), b(t)\}$, which is the discrete time Markov chain depicted in Figure 3-4, with the following transition probabilities.[6, 12]

$$P\{i, k|i, k+1\} = 1, \quad k \in [0, W_i - 2], i \in [0, m] \quad (3-8a)$$

$$P\{0, k|i, 0\} = \frac{1-p}{W_0}, \quad k \in [0, W_i - 1], i \in [0, m-1] \quad (3-8b)$$

$$P\{i, k|i-1, 0\} = \frac{p}{W_i}, \quad k \in [0, W_i - 1], i \in [1, m] \quad (3-8c)$$

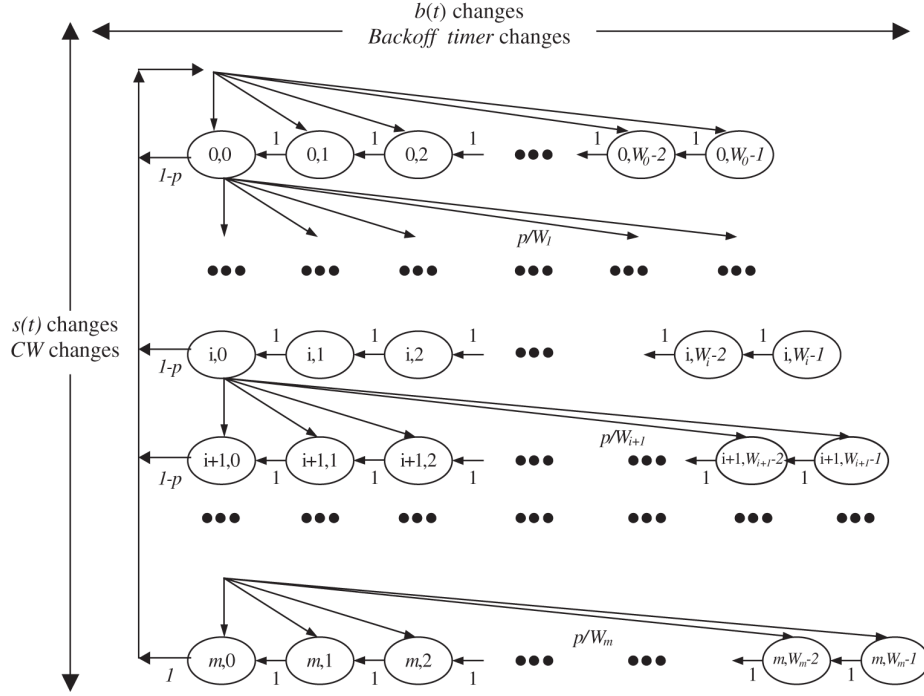


Figure 3-4: Markov Chain Model used to model CSMA/CA.[12]

$$P\{0, k|m, 0\} = \frac{1}{W_0}, \quad k \in [0, W_m - 1], i = m \quad (3-8d)$$

These transitions probability represent:

- Decrement of the back-off window time counter (Eq. 3-8a);
- A successful transmission ends up into a new transmission at a back-off stage 0 (Eq. 3-8b);
- An unsuccessful transmission at back-off stage $i - 1$ leads to a uniform random chosen back-off window in the range $[0, W_i - 1]$ at back-off stage i (Eq. 3-8c).
- An unsuccessful transmission at the last back-off stage m leads to reset of the back-off window to W_0 and going back to the first back-off stage (Eq. 3-8d).

For the stationary distribution on the Markov chain the next notation is used: $b_{i,k} = \lim_{t \rightarrow \infty} P\{s(t) = i, b(t) = k\}$ where $i \in (0, m)$ and $k \in (0, W_i - 1)$. This leads to the following equations to describe the behaviour of $b_{i,0}$.

$$b_{i,0} = p^i \cdot b_{0,0}, 0 < i \leq m \quad (3-9)$$

The values for $b_{i,k}$ are given by the next equation.

$$b_{i,k} = \frac{W_i - k}{W_i} \cdot b_{i,0}, \quad 0 \leq i \leq m, 0 \leq k \leq W_i - 1 \quad (3-10)$$

Equations 3-9 and 3-10 give an expression for all values of $b_{i,k}$ as function of $b_{0,0}$ and p . The summation of the probabilities for all the states should be equal to 1. Using this property $b_{0,0}$ can be determined by the following:

$$\begin{aligned} 1 &= \sum_{i=0}^m \sum_{k=0}^{W_i-1} b_{i,k} = \sum_{i=0}^m b_{i,0} \cdot \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} = \sum_{i=0}^m b_{i,0} \cdot \frac{W_i + 1}{2} \\ &= \sum_{i=0}^m p^i \cdot b_{0,0} \cdot \frac{W_i + 1}{2} = \frac{b_{0,0}}{2} \left(\sum_{i=0}^m p^i \cdot W_i + \sum_{i=0}^m p^i \right) \\ &= \frac{b_{0,0}}{2} \left[\sum_{i=0}^m ((2p)^i \cdot W_0) + \sum_{i=0}^m p^i \right] = \frac{b_{0,0}}{2} \left[\frac{1 - (2p)^{m+1}}{1 - (2p)} W_0 + \frac{1 - p^{m+1}}{1 - p} \right] \end{aligned} \quad (3-11)$$

Leading to:

$$b_{0,0} = \frac{2(1 - 2p)(1 - p)}{W_0(1 - (2p)^{m+1})(1 - p) + (1 - 2p)(1 - p^{m+1})} \quad (3-12)$$

The probability that a device transmits in a random chosen slot time is given as τ . Transmission of a packet occurs when the back-off timer equals to zero, irrespective of the back-off stage. This means that transmissions occur at every $\{i, 0\}$ state. Using the Markov Chain Model, the probability of transmission is the sum of all the $\{i, 0\}$ states:

$$\tau = \sum_{i=0}^m b_{i,0} = \sum_{i=0}^m p^i \cdot b_{0,0} = b_{0,0} \frac{1 - p^{m+1}}{1 - p} \quad (3-13)$$

From this equation $b_{0,0}$ can be calculated using Equation 3-12. Furthermore Equations 3-13 and 3-12 shows that τ depends on the minimum window size W_0 , the maximum number of retransmissions m , and the probability of a collision p , which is still unknown.

Next the probability of a collision p will be discussed. A packet transmitted by a node collides when at least one other device also transmit a packet. When directional antennas are used it means that a collision occurs when two or more devices are transmitting in the same direction. This can mathematically be described as:

$$p = 1 - \left(1 - \frac{1}{N_s} \tau \right)^{n-2} (1 - \tau) \quad (3-14)$$

This means that the probability of a collision p depends on the number of antenna sectors N_s , the number of nodes in the network n and the probability of a transmission τ . The

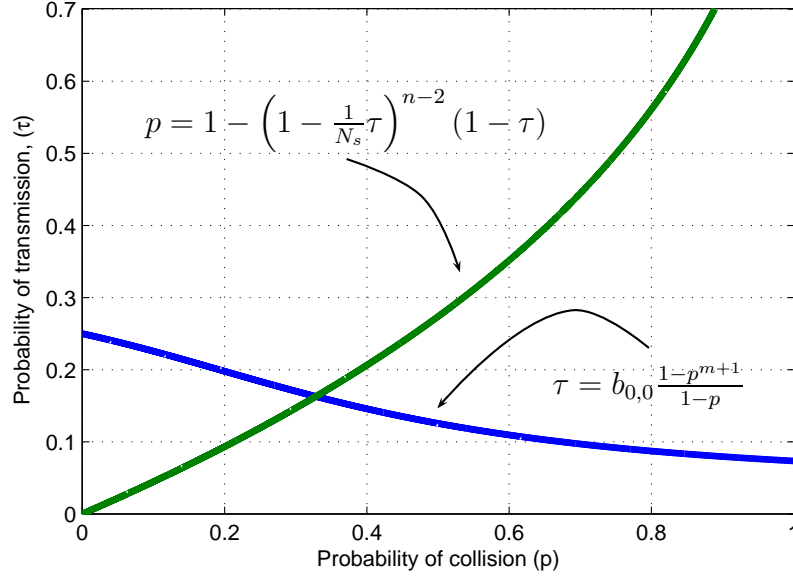


Figure 3-5: An example of values for τ for different values of p using Equation 3-14 and Equation 3-13. The next parameters are used: $N_s = 6, n = 10, m = 3$ and $W_0 = 7$

probability of transmission and the probability of collision are related with each other. Equations 3-13 and 3-14 form a nonlinear system with two unknown p and τ which can be solved using numerical methods and has a unique solution.[11] This means that for every given network there will be a solution unique to that network. If the network for example changes by adding another node, the solution to the equations will also change. An example of the relation between Equations 3-13 and 3-14 is shown in Figure 3-5.

Delay Successful Transmission

The MAC delay D of a successful transmission is the time from which the packet is at the head of the MAC queue until an acknowledgement of the packet. The delay of collided packets or dropped packets are not calculated. The average delay ($E[D]$) is given as the average number of slot times needed ($E[N_{slot}]$) multiplied by the average length of a slot time ($E[L_{slot}]$).[6, 12] This is given in Equation 3-15.

$$E[D] = E[N_{slot}]E[L_{slot}] \quad (3-15)$$

The average number of slots needed is the number of slots (d_i) a packet needs in the i^{th} back-offstage times the probability (q_i) that a not dropped packet reaches the i^{th} back-offstage. Here the average slots (d_i) a device uses is given by

$$d_i = \frac{W_i + 1}{2}, \quad i \in [0, m] \quad (3-16)$$

Moreover the probability that a packet which not has been discarded reaches the i^{th} back-offstage is equal to

$$q_i = \frac{p^i - p^{m+1}}{1 - p^{m+1}}, \quad i \in [0, m] \quad (3-17)$$

where p^{m+1} equals to the probability that a packet is dropped. This leads for the average number of slots needed to

$$E[N_{slot}] = \sum_{i=0}^m \left(\frac{W_i + 1}{2} \cdot \frac{p^i - p^{m+1}}{1 - p^{m+1}} \right) \quad (3-18)$$

The average length of a slot time $E[L_{slot}]$ is dependent upon the probability of a transmission in a given slot time P_{tr} , the probability of a successful transmission P_s , the idle slot time σ , the duration of a successful transmission T_s and the duration of a collided transmission T_c . These slot times are not real slots of the MAC protocol, it rather is a “virtual” slot used to calculate the delay more easily. Equation 3-19 shows the formula for the average length of a slot time.

$$E[L_{slot}] = (1 - P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1 - P_s)T_c \quad (3-19)$$

Where P_{tr} means that at least one device transmits a packet in the considered slot time and is thus given as

$$P_{tr} = 1 - (1 - \tau)^n \quad (3-20)$$

A transmission is successful when exactly one device transmits, one device is able to receive the transmission and all other devices defer transmission in the direction of the transmission.

$$P_s = \frac{n\tau \left(1 - \frac{\tau}{N_s}\right)^{n-2} (1 - \tau)}{P_{tr}} \quad (3-21)$$

Delay Route Discovery Process

The total round trip time of equals to the delay for the RREQ added with the delay caused by the RREP. This means that Equation 3-1, $E[RTT] = E[D_{RREQ}] + E[D_{RREP}]$, is also valid for ongoing traffic conditions. However the delay for the RREQ $E[D_{RREQ}]$ and the delay for the route reply $E[D_{RREP}]$ are different from the non ongoing traffic conditions. The average delay for RREQ now becomes the number of hops (N_h) times the average number of transmissions ($E[N_{tx}]$) times the average delay ($E[D]$):

$$E[D_{RREQ}] = N_h E[N_{tx}] E[D] = N_h E[N_{tx}] E[N_{slot}] E[L_{slot}] \quad (3-22)$$

Since broadcasting does not have any feedback on collisions there are no retransmissions. This means m is zero leading to to following expected number of slots needed:

$$E[N_{slot}] = \sum_{i=0}^0 \left(\frac{W_i + 1}{2} \cdot \frac{p^i - p}{1 - p} \right) = \frac{W_0 + 1}{2} \quad (3-23)$$

Table 3-3: The the values of different parameters used for the mathematical result. These values are specifically for the mmWave WPAN route discovery.

Parameter	Value
T_{sl} , Duration of BIFS/idle slot	1.2 microseconds
T_{sifs} , Duration of SIFS	0.9 microseconds
T_{tx} , Duration of transmission	0.308 microseconds
W_0 , Back-off windows size	8
m , Maximum retransmissions	3

For the mmWave WPAN the duration of a successful transmission almost equals the duration of a collided transmission. When $T_s \approx T_c$ Equation 3-19 simplifies into:

$$E[L_{slot}] = (1 - P_{tr})\sigma + P_{tr}T_s \quad (3-24)$$

The average duration of the slot time becomes:

$$E[L_{slot}] = (1 - P_{tr})T_{sl} + P_{tr}(T_{sifs} + T_{tx}) \quad (3-25)$$

Resulting into:

$$E[D_{RREQ}] = N_h \cdot \frac{N_s + 1}{2} \cdot \frac{W_0 + 1}{2} \cdot \{(1 - P_{tr})T_{sl} + P_{tr}(T_{sifs} + T_{tx})\} \quad (3-26)$$

The average delay for the route reply is now given as:

$$E[D_{RREP}] = N_h E[N_{slot}] E[L_{slot}] \quad (3-27)$$

Unlike the RREQ retransmissions should be considered for the RREP. The maximum number of retransmissions equals to 3, thus $m = 3$. The average length of a slot is the same as the RREQ. This means that $E[D_{RREP}]$ can be calculated as

$$E[D_{RREP}] = N_h \cdot \left[\sum_{i=0}^3 \left(\frac{W_i + 1}{2} \cdot \frac{p^i - p^4}{1 - p^4} \right) \right] \cdot \{(1 - P_{tr})T_{sl} + P_{tr}(T_{sifs} + T_{tx})\} \quad (3-28)$$

3-2-2 Results

Like in Section 3-1 the beamwidth of the antenna and the number of hops between the source and the destination is varied. Table 3-3 shows the values for different parameters used in the mathematical model. Where possible same values are used for the simplified mathematical model without traffic and the extended mathematical model under saturated traffic conditions.

In order to model rooms, small piconets are joined together. For every hop another piconet is accessed. For the mathematical model this means that every hop contains a number of

nodes which are in steady state. Figures 3-6, 3-7 and 3-8 show the results of varying antenna beamwidth and number of hops for different sizes of the network. Figure 3-6 shows results for a node density of 5 nodes. Figure 3-7 shows the situation for a node density 9. Results for a piconet consisting of 100 nodes for every hop is displayed in Figure 3-8. From these figures it can be observed that the extended model has the following behaviour. An increasing beamwidth leads to a decreasing RTT, provided that the transmission range of the different beamwidths does not change. Raising the number of hops leads to an increasing RTT. Furthermore from these figures it can be noticed that an increase in size of a network leads to a higher RTT. This increase is relatively higher as the antenna beamwidth increases, again provided that the transmission range does not change. Smaller antenna beamwidth are relatively less dependent upon the number of nodes in the network under the assumption that decreasing the antenna beamwidth does not increase the transmission range.

Figure 3-9 shows the RTT for the lower bound derived in Section 3-1 and the RTT for the upper bound as derived in Section 3-2. It should be noted that these bounds do not represent the minimum delay and the maximum RTT. It does however give an indication on the expected delay for low traffic conditions and the expected delay for high traffic conditions. From Figure 3-9 it can also be observed that an increase in the number of nodes in the network does not have an increasing effect on the RTT for the lower bound. It does however have an increasing effect on the RTT for the upper bound.

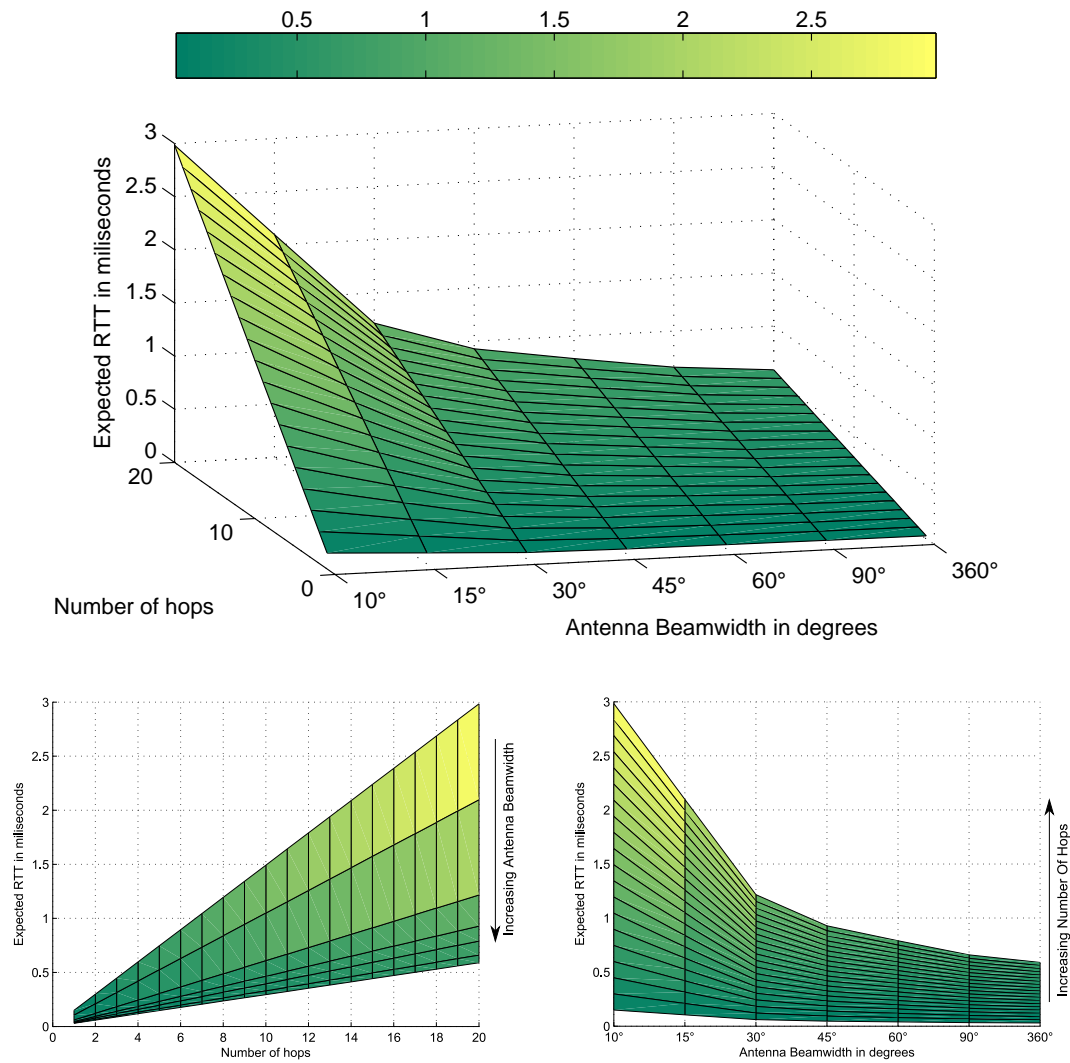


Figure 3-6: Results of the mathematical model for a network with a node density of 5 nodes per hop. The RTTs are based on the parameters given in Table 3-3.

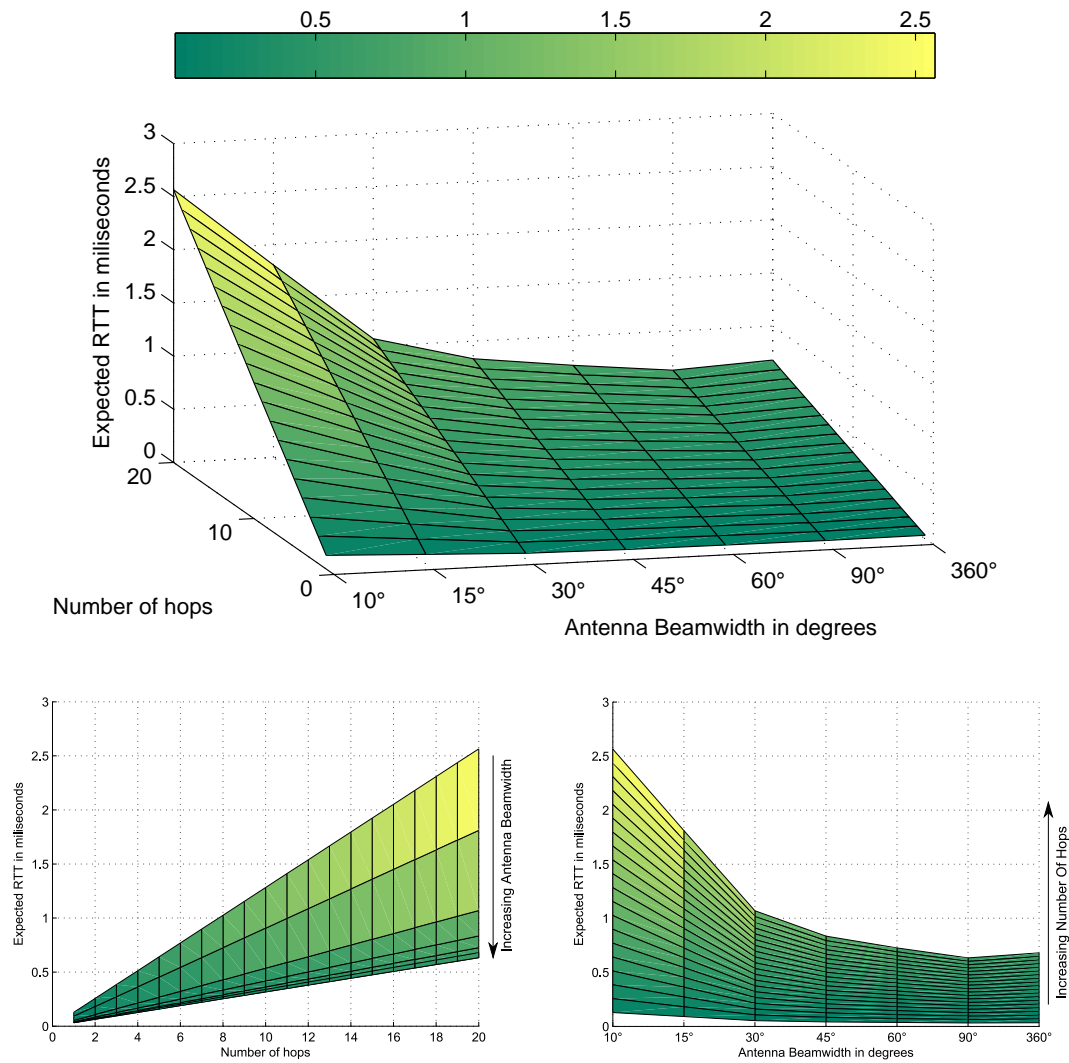


Figure 3-7: Results of the mathematical model for a network with a node density of 9 nodes per hop. The RTTs are based on the parameters given in Table 3-3.

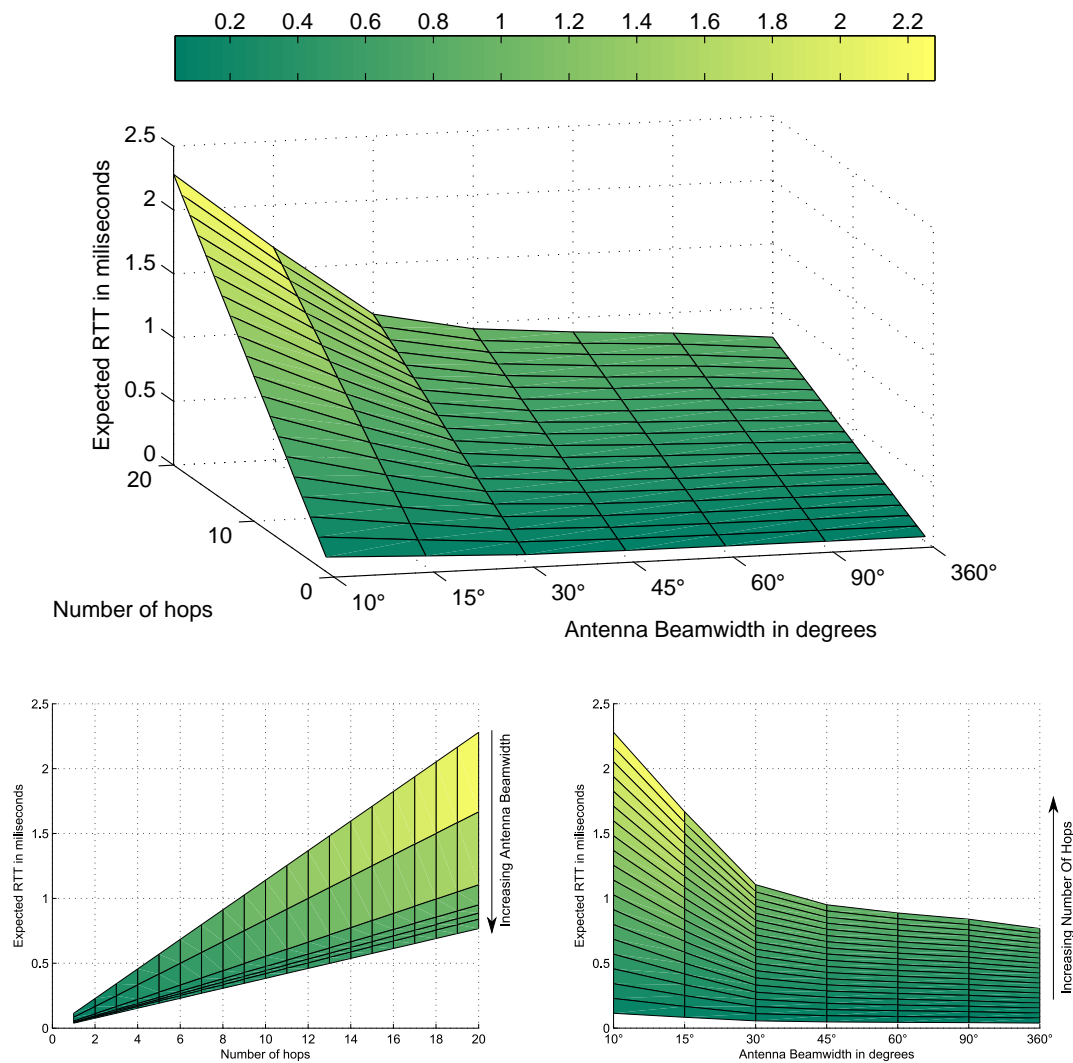
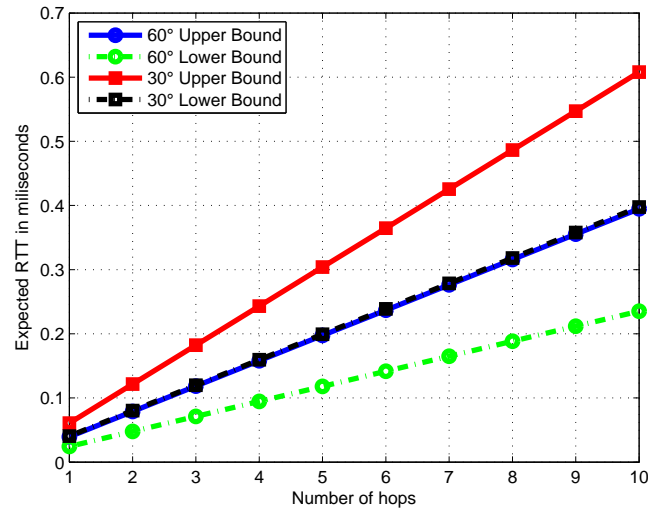
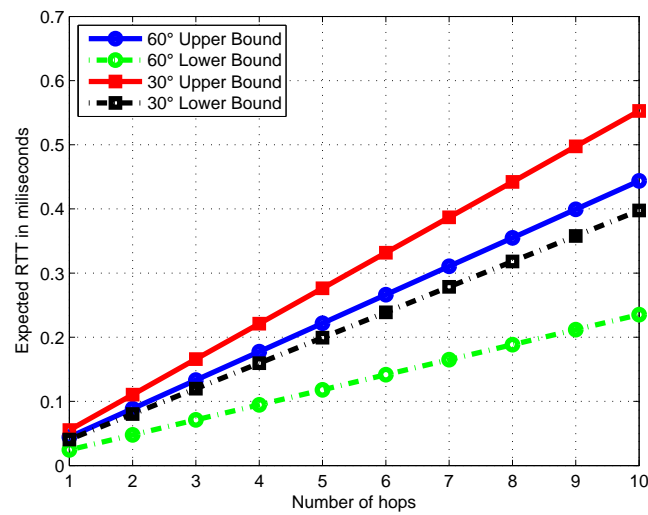


Figure 3-8: Results of the mathematical model for a network with a node density of 100 nodes per hop. The RTTs are based on the parameters given in Table 3-3.



(a) 5 Nodes



(b) 100 Nodes

Figure 3-9: The RTT lower bound resulting from the simplified model and the RTT upper bound resulting from the saturated traffic model for 5 and 100 nodes in a network.

3-3 Conclusions

In this chapter two mathematical models to calculate the route discovery delay have been derived. From this chapter the subsequent conclusions can be drawn.

- The average round trip time for a route discovery process equals to the route request delay added with the route reply delay. Hence the average delay is given by $E[RTT] = E[D_{RREQ}] + E[D_{RREP}]$
- The values for $E[D_{RREQ}]$ and $E[D_{RREP}]$ depends on the traffic, network topology, antenna beamwidth and the number of hops.
- Generally a larger network leads to a higher delay compared with a smaller network.
- An expansion of the network with more nodes leads to a relatively higher delay for larger antenna beamwidths with the same transmission range.
- Incrementing the number of hops causes an increase in the RTT.
- Using smaller antenna beamwidths usually leads to a higher transmission range. To see the influence of the number of directions to transmit to, this increased range is not considered in the mathematical model. Decreasing the antenna beamwidth while maintaining the transmission range, results into a higher average RTT.
- An increase in the number of nodes in the network does not have an increasing effect on the RTT for the lower bound. The influence of the node density for the upper bound depends on the antenna beamwidth. For the mathematical model with the parameters used in Table 3-3 smaller beamwidths lead to a reduced RTT, where beamwidths over 45° lead to a higher RTT. This effect results from the values of σ and T_s from Equation 3-24, where $\sigma < T_s$. An increase in the node density would automatically lead to an increase in the RTT, in case $\sigma > T_s$.

Chapter 4

Simulation

This chapter discusses the simulations. All the simulations are done using the OPNET Modeler[®] software created by OPNET Technologies [3]. The data obtained from the simulations are processed using Matlab and Excel. The goals for the simulations are to get a better insight into the following:

- The influence of the number of hops on the RTT.
- The influence of the forwarding algorithm on the RTT.
- The influence of the antenna beamwidth on the RTT.
- The influence of the mean node degree on the RTT.

In order to achieve these goals different scenarios are simulated. This chapter is organised as follows. First the simulation software is described in Section 4-1, followed by Section 4-2 containing the simulation scenarios and their configuration. Next in Section 4-3 the simulations are analysed; ending the chapter with the conclusions in Section 4-4.

4-1 Simulation Software

For the simulations OPNET Modeler[®] will be used. OPNET Modeler[®] is a discrete event simulator developed by OPNET Technologies. Besides OPNET Modeler[®], OPNET technologies provides other software used for networking such as network planning tools. The main focus on OPNET Modeler[®] is to provide a networking tool for Research & Development. To add more functionality to OPNET Modeler[®] different modules may be

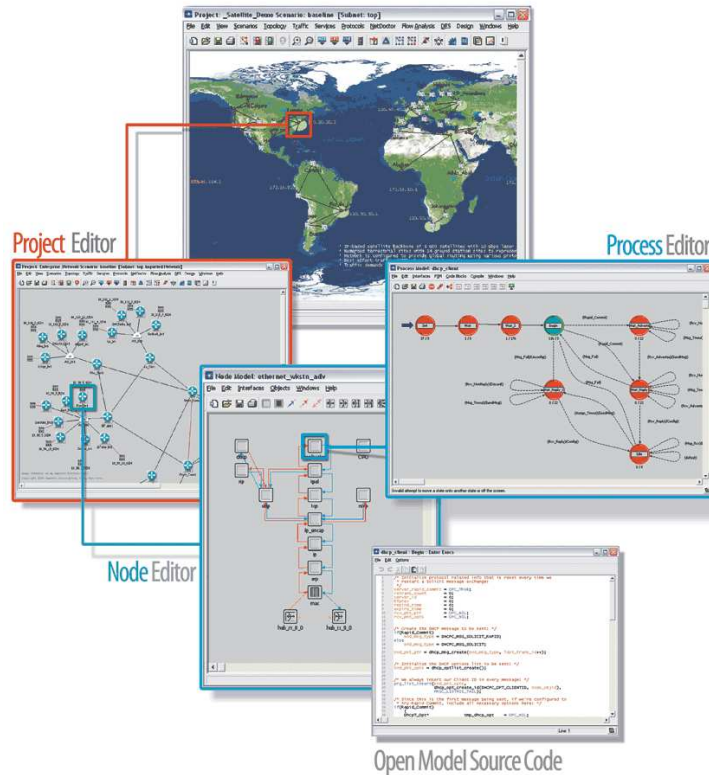


Figure 4-1: The architecture of OPNET Modeler®, consisting of the Project Editor, the Node Editor and the Process Editor.[3]

added. In order to simulate wireless applications OPNET Modeler® needs the Wireless Module. Using this module enables features such as antenna and mobile nodes.[3]

The modelling architecture of OPNET Modeler® is hierarchical and consists of three major environments. At the highest level there is the Project Editor, followed by the Node Editor. The Process Editor is at the lowest level. Figure 4-1 shows these different environment. A summation is explained below.[3]

- Project Editor (Figure 4-2). The project editor represents the topology of a network. In this editor the position of different nodes can be set and different links can be established. Besides setting the nodes and links, the physical size of the network can be set. A project can contain different scenarios to compare various set-ups.
- Node Editor (Figure 4-3). The node editor is used to create or edit network devices, by connecting different modules with each other. The modules represent protocols and algorithms. To organise the modules better, the different modules are usually hierarchically placed, as shown in Figure 4-3 for a WLAN node.

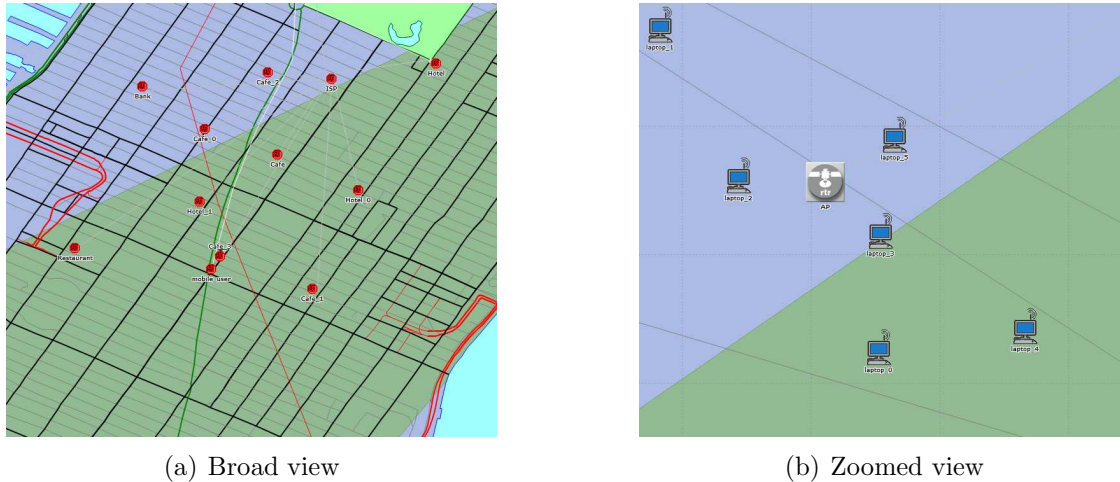


Figure 4-2: The Project Editor in OPNET Modeler®. Here different devices, also called nodes, are placed to create different scenarios. The broad view shows subnets in Manhatan, New York City. The zoomed view shows the subnets containing access points and wireless laptops

- **Process Editor** (Figure 4-4). The process editor uses Finite State Machines (FSMs) to implement protocols and algorithms used for the node model. At the states various actions can be programmed. The transition between the various states can be regulated by defining different events. Also when going from one state to another state a function can also be executed. The first state always is the init state.

Besides these three major domains in OPNET Modeler® there are also some smaller domains. The most some examples which also have been used for this thesis are:

- **Packet Format Editor:** In this editor a packet format can be implemented. The packet formats contain different fields with a particular size. There are various types of fields. A field can for example be an integer, a floating point, a structure or even a packet.
- **Antenna Pattern Editor:** The Antenna Pattern Editor enables users to create an antenna pattern. A antenna pattern is implemented by setting a gain for various values of the azimuth angle (ϕ) and the elevation angle (θ).

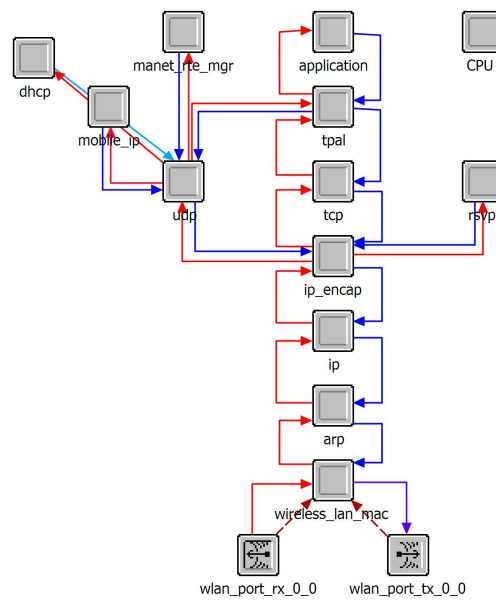


Figure 4-3: The Node Model Editor environment for in this case a WLAN device. A node consists of different projects connected with each other. To have a better structure the processes are stacked according to the OSI layer model.

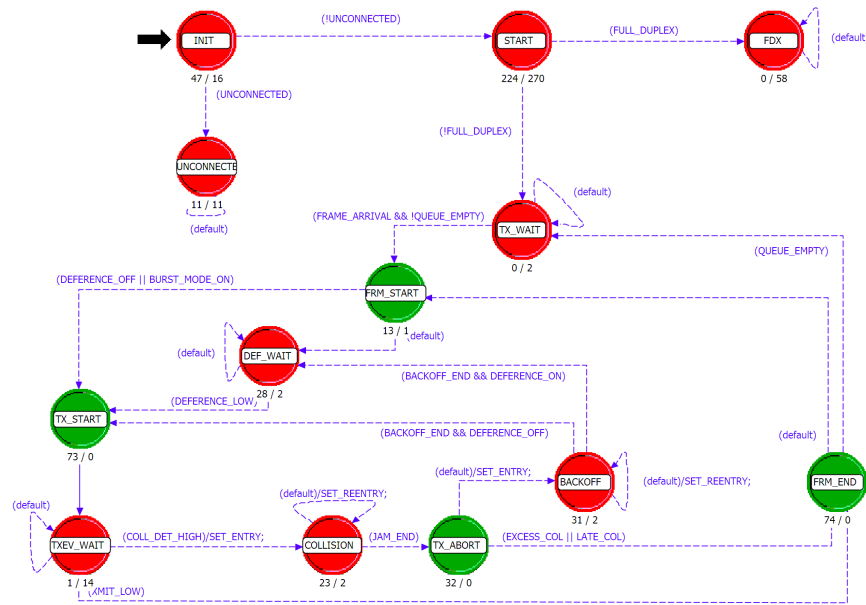


Figure 4-4: An example of a process inside the Process Editor. A process contains different states, transitions and actions to be taken. For this figure a CSMA/CA process is used as example.

4-1-1 Wall Principle

Although OPNET Modeler® has many features, it has some shortcomings when it comes to the indoor environment. For WPANs the indoor environment is very important, as the application is most of the times also indoors. Important aspects of indoor environments are for example different objects in a room, windows, and more importantly walls. The objects, windows and walls cause attenuation and reflection of the signals. Because of the low power WPAN devices use to transmit, the reflection and attenuation have a bigger impact compared with for example cellular networks.

An office environment without any objects and walls can be created in the Project Editor of OPNET Modeler®. But because of limitations of OPNET Modeler® itself walls and thus rooms cannot be created with the Project Editor. To overcome this problem the physical model of the mmWave WPAN in OPNET Modeler® has been changed. Normally the received power P_r depends on the path loss L_p , this means: $P_r \propto L_p$. Walls cause extra attenuation and lower the power received. In OPNET Modeler® this extra attenuation was subtracted from the received power at the distance of the wall, giving $P_r \propto L_p - L_w$; where L_w equals to the losses due to walls. These losses are dependent on the distance. If the distance of the wall is 6 meters, L_w equals to 0dB for distances shorter than 6 meters, 12dB for distances larger than 6 meters and 24dB for distances larger than 12 meters. Resulting into an extra 12dB loss for every 6 meters.

4-2 Simulation Scenarios

For the simulation different scenarios are used. Table 4-1 shows the different specifications and the network configuration for those scenarios. The names for these scenarios are given according to the following scheme: **Name Scenario = Number Of Hops + Algorithm Used + Antenna Beamwidth + Network Configuration**. A scenario with four hops, forwarding Algorithm 0, an antenna beamwidth of 60° and a straight line topology is called H4_A0_60D_SL. In the next subsections the different configurations used for the scenarios will be described.

4-2-1 Number Of Hops

The number of hops depends on the minimal hops the RREQ and RREP message have to take to be received at their destination. One hop means that a RREQ will be transmitted to a direct neighbour. Depending on the topology of the network, a RREP may contain a path with more hops than the minimal number of hops. These packages are discarded, since they do not contain the shortest route, even though they may be received sooner.

Table 4-1: The different scenarios for the simulations and their configuration

Simulation Set	Name	Minimal Hopcount	Forwarding Algorithm	Antenna Beamwidth	Network Configuration
Set #1	H1_A0_60D_SL	1	0	60°	Straight Line
	H2_A0_60D_SL	2	0	60°	Straight Line
	H3_A0_60D_SL	3	0	60°	Straight Line
	H4_A0_60D_SL	4	0	60°	Straight Line
Set #2	H4_A0_60D_SL	4	0	60°	Straight Line
	H4_A1_60D_SL	4	1	60°	Straight Line
	H4_A2_60D_SL	4	2	60°	Straight Line
	H4_A0_30D_SL	4	0	30°	Straight Line
	H4_A1_30D_SL	4	1	30°	Straight Line
	H4_A2_30D_SL	4	2	30°	Straight Line
Set #3	H4_A0_60D_M1	4	0	60°	Mesh Network #1
	H4_A1_60D_M1	4	1	60°	Mesh Network #1
	H4_A2_60D_M1	4	2	60°	Mesh Network #1
	H4_A0_30D_M1	4	0	30°	Mesh Network #1
	H4_A1_30D_M1	4	1	30°	Mesh Network #1
	H4_A2_30D_M1	4	2	30°	Mesh Network #1
Set #4	H4_A0_60D_M2	4	0	60°	Mesh Network #2
	H4_A1_60D_M2	4	1	60°	Mesh Network #2
	H4_A2_60D_M2	4	2	60°	Mesh Network #2
	H4_A0_30D_M2	4	0	30°	Mesh Network #2
	H4_A1_30D_M2	4	1	30°	Mesh Network #2
	H4_A2_30D_M2	4	2	30°	Mesh Network #2

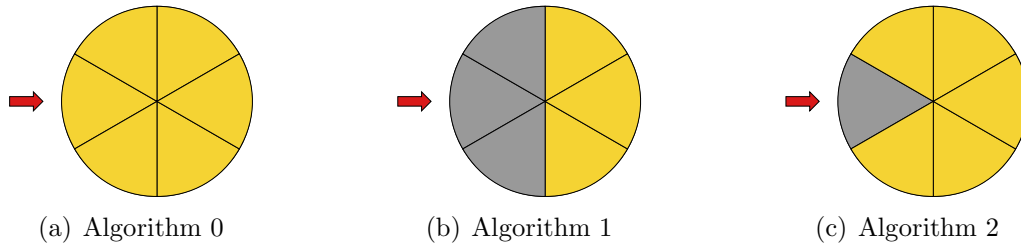


Figure 4-5: The different forwarding algorithms used in the simulation. Yellow indicates transmitting sectors, grey indicates silent sectors. The arrow indicates the direction of reception. Algorithm 0 transmits the route request in all directions. Algorithm 1 does not transmit in the direction of reception and the two sectors next to it. Algorithm 2 transmits in all directions except of the direction of reception.

4-2-2 Forwarding Algorithms

There are three algorithms used for forwarding data, which are illustrated in Figure 4-5. The purpose of these forwarding algorithms is trying to optimise the route discovery.

1. **Algorithm 0 (Figure 4-5(a))** First there is Algorithm 0, which has this name since no special algorithm is used for forwarding. In this algorithm route requests are transmitted in all directions, irrespective of the direction of reception.
2. **Algorithm 1 (Figure 4-5(b))** For the second algorithm, Algorithm 1, the direction of reception and the two adjacent directions are discarded.
3. **Algorithm 2 (Figure 4-5(c))** The last algorithm, Algorithm 2, transmits the route requests in all directions except for the direction of reception.

In the previous chapter it is shown that the RTT depends on the number of transmissions. The idea behind Algorithm 1 and Algorithm 2 is that since the destination is not in the path of the transmitter and the receiving node, that path is obsolete. This should lead to less redundant transmissions and thus a faster route discovery.

4-2-3 Antenna Beamwidth

For the different scenarios two antennas are used to see the influence of the antenna beamwidth. Both of the antennas have an antenna pattern in the shape of a cone, not containing any side-lobes. The difference between the antennas is the antenna beamwidth, which are 60° and 30° . The gain at the maximum is the same, so the antennas will have the same transmission range. Although this is not realistic, since a smaller beamwidth has a higher gain in real life situations, it will illustrate the influence of the number of sectors to transmit to better.

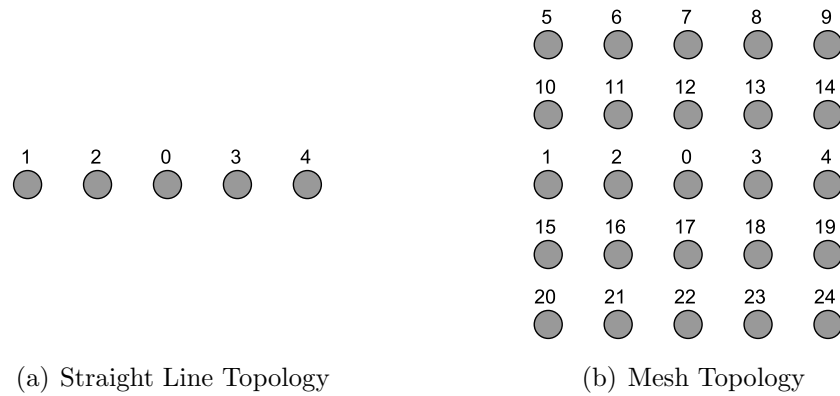


Figure 4-6: The different network topologies used for the simulations. The number indicates the node's MAC address; the node with MAC address 0 is the preassigned PNC.

4-2-4 Simulation Topology

There are in total three different topologies used for the simulation.

1. **Straight Line.** In this topology five devices are put in a straight line. The distance between all the devices is five meters. Figure 4-6(a) shows the straight line topology. The communication range is about 6 meters, after this distance the power decreases significantly. Figure 4-7(a) shows which neighbouring devices can be reached. The communication range and the network topology result into Figure 4-8(a).
2. **Mesh Network #1.** A total of 25 devices are put in a grid topology. Figure 4-6(b) shows the topology of the network. Using the wall principle explained earlier in this chapter, the communication range is again set at 6 meters, as shown in Figure 4-7(a). Resulting into a minimum of two neighbours and a maximum of four neighbours, with a mean node degree of 3.2. The communication range and the network topology result into Figure 4-8(b).
3. **Mesh Network #2.** A total of 25 devices are put in a grid topology as displayed in Figure 4-6(b). This time the transmission range is increased to 8 meters. Leading to an augmentation of the number of neighbours as shown in Figure 4-7(b). The mean node degree also increases and becomes 5.76. The minimum number of neighbours equals to three, the maximum equals to eight. The communication range and the network topology result into Figure 4-8(c).

4-3 Simulation Analysis

The next subsections describe the different simulation sets. For every simulation run 1000 route discovery processes are initialised and processed.

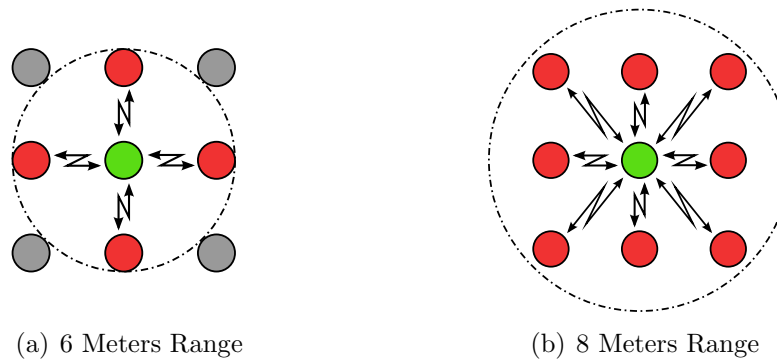


Figure 4-7: The different ranges of communication used for the simulation. The green node is the transmitting node; the red nodes are the nodes able to receive transmissions; the grey nodes do not receive messages from the transmitter.

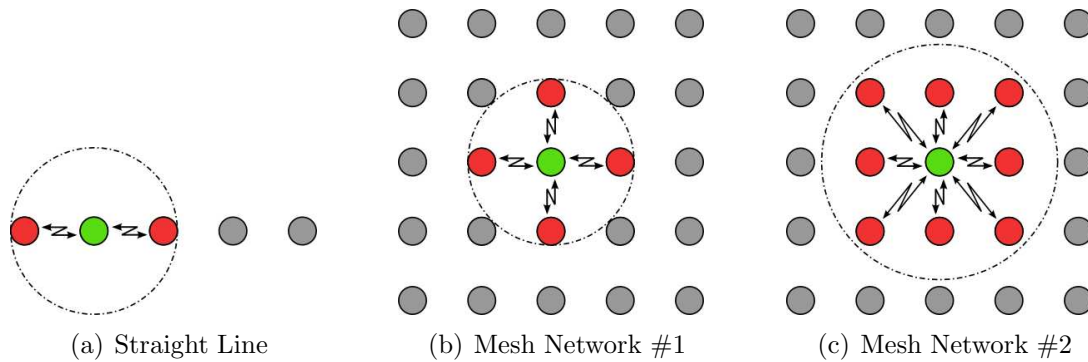
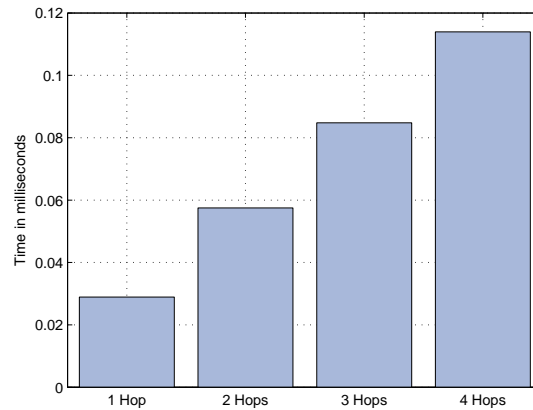


Figure 4-8: The resulting network topologies and ranges. The green node is the transmitting node; the red nodes are the nodes able to receive transmissions; the grey nodes do not receive messages from the transmitter.

Table 4-2: Results for Simulation Set #1

Name	RTT in milliseconds			
	Mean	Std	Max	Min
H1_A0_60D_SL	0.0289	0.0123	0.0582	0.0056
H2_A0_60D_SL	0.0575	0.0179	0.1172	0.0159
H3_A0_60D_SL	0.0848	0.0207	0.1476	0.0335
H4_A0_60D_SL	0.1139	0.0243	0.1910	0.0378

**Figure 4-9:** Mean RTT for a straight line topology network with a beamwidth of 60 degrees.

4-3-1 Simulation Set #1

This simulation is done in order to see the influence of the number of hops on the RTT using a straight line topology. Using a maximum of five devices a maximum of four hops is achieved. The beamwidth of the antenna is fixed and set at 60 degrees. Furthermore Algorithm 0 is used as forwarding algorithm. The results for this simulation are given in Table 4-2. Figure 4-9 shows the different mean times needed for the Route Request process. A histogram for the different number of hops is given in Figure 4-10.

From Figure 4-9 and Table 4-2 it can be observed that the mean RTT depends linearly on the number of hops. Figure 4-10 shows that the times of arrival behave like a normal distribution, with an increasing mean and standard deviation as the number of hops also increases.

4-3-2 Simulation Set #2

Simulation Set #2 also uses the straight line topology Simulation Set #1 uses. For Simulation Set #2 the number of hops is fixed at four hops and the distance between two devices is also fixed at five meters. The forwarding algorithm and the antenna beamwidth

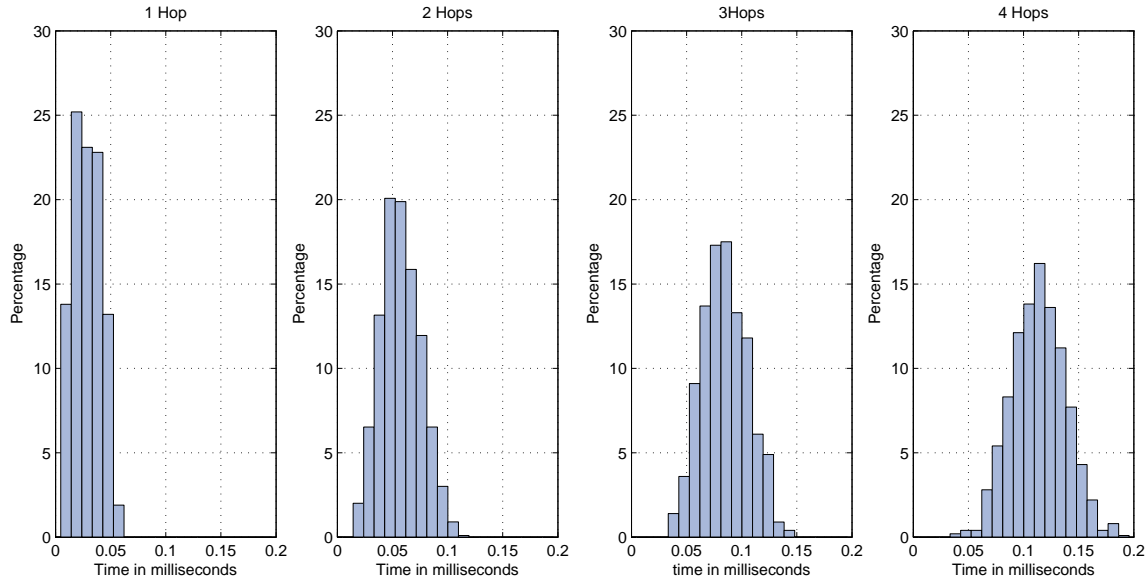


Figure 4-10: Time of arrival for different hops.

Table 4-3: Results for Simulation Set #2

Name	RTT in milliseconds			
	Mean	Std	Max	Min
H4_A0_60D_SL	0.1139	0.0243	0.1910	0.0378
H4_A1_60D_SL	0.0856	0.0154	0.1376	0.0395
H4_A2_60D_SL	0.1042	0.0209	0.1639	0.0486
H4_A0_30D_SL	0.1892	0.0466	0.3188	0.0716
H4_A1_30D_SL	0.1616	0.0348	0.2994	0.0366
H4_A2_30D_SL	0.1808	0.0415	0.3105	0.0586

are changed. Table 4-3 shows the results for this simulation set. The mean times are also depicted in Figure 4-11, the times of arrival are shown in Figure 4-12.

The mean times for 60° beamwidth are lower then those for the 30° beamwidth. The times for Algorithm 1 are the lowest followed by Algorithm 2. For the 60° beamwidth the ratio between the algorithms is larger compared with the 30° beamwidth. This means that the influence of different forwarding algorithms is better noticeable for smaller antenna beamwidths. The times of arrival depicted in Figure 4-12 have the shape of a normal distribution.

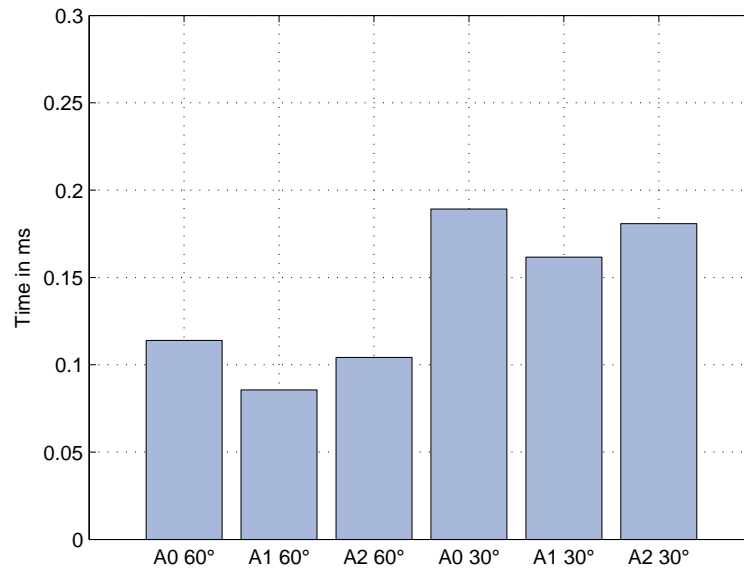


Figure 4-11: The mean delay for Simulation Set #2.

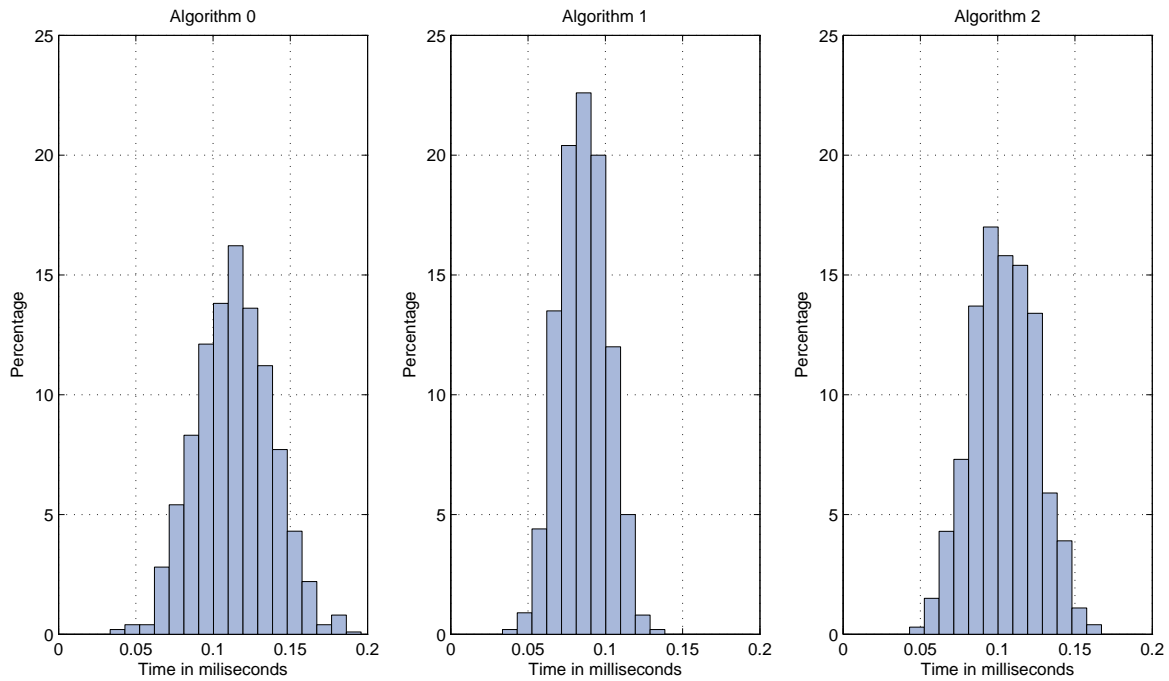
4-3-3 Simulation Set #3

Simulation Set #3 is a network consisting of 25 devices placed in a 5-by-5 grid topology. The distance between each device is five meters, resulting in a network which is 25 meters by 25 meters. The nodes can only communicate with neighbours which are within 6.5 meters. A larger distance would result in a SNR too low to be useful. There is only one shortest path which has a hopcount of four hops. This network topology is called **Mesh Network #1**. Results for this simulation set are given in Table 4-4. The mean times are shown in Figure 4-13.

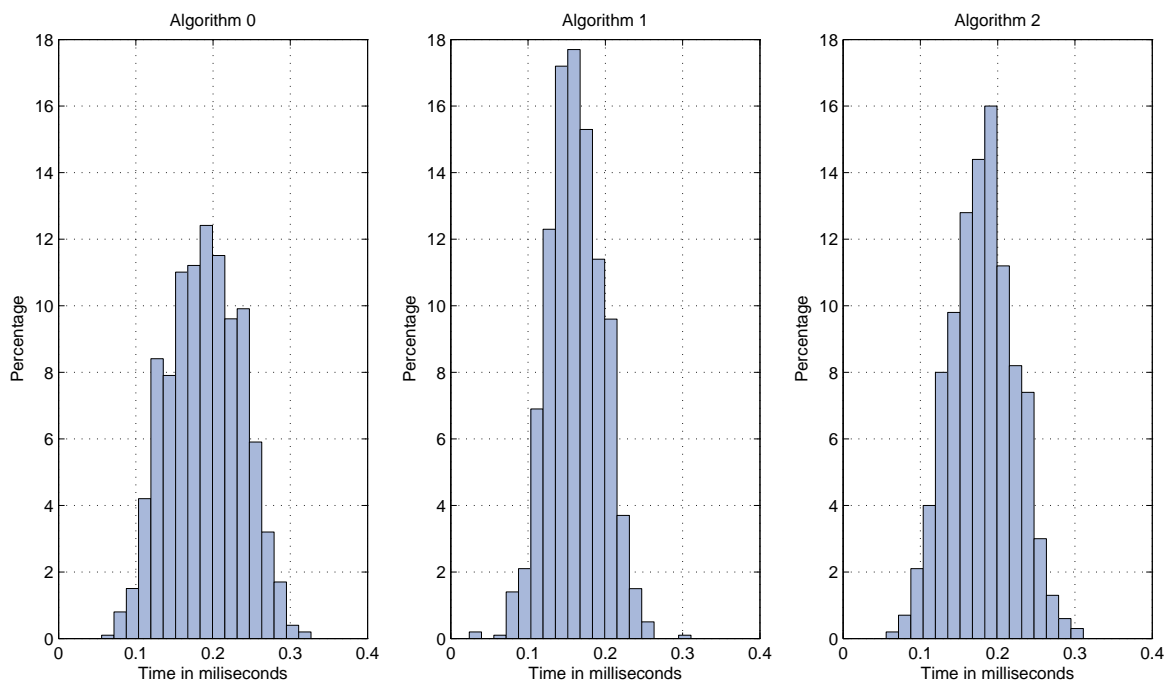
Figure 4-13 shows that the increased size of the network has led to slightly higher mean RTT compared with Figure 4-11. However the maximum RTT has increased considerably. The rest of the behaviour is the same as the four hop straight topology. Meaning that the 60° beamwidth performs better compared with the 30° beamwidth and Algorithm 1 performs best, followed by Algorithm 2. The normally distributed RTTs from Simulation Set #2 are not present anymore.

4-3-4 Simulation Set #4

Like Simulation Set #3, Simulation Set #4 also consists of 25 devices placed in a grid topology, with a distance of five meters between the devices. However the range of communication has increased from 6.5 meters to 8 meters. This increase of range has the effect



(a) 60° beamwidth

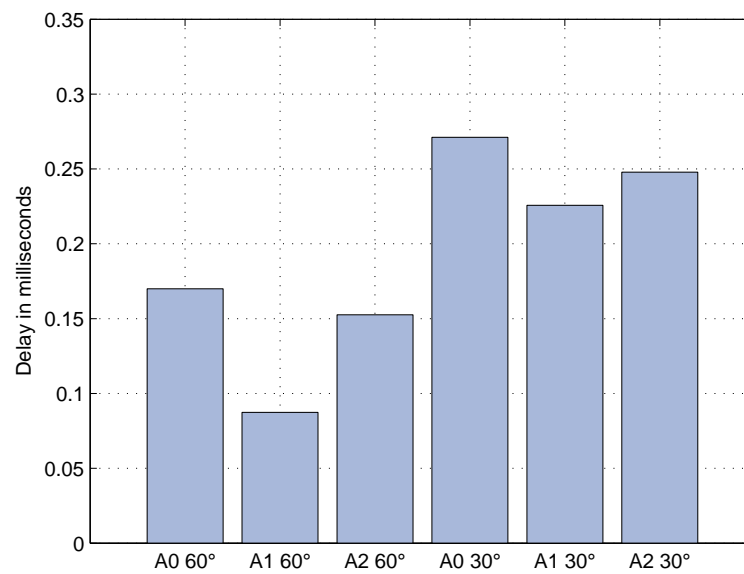


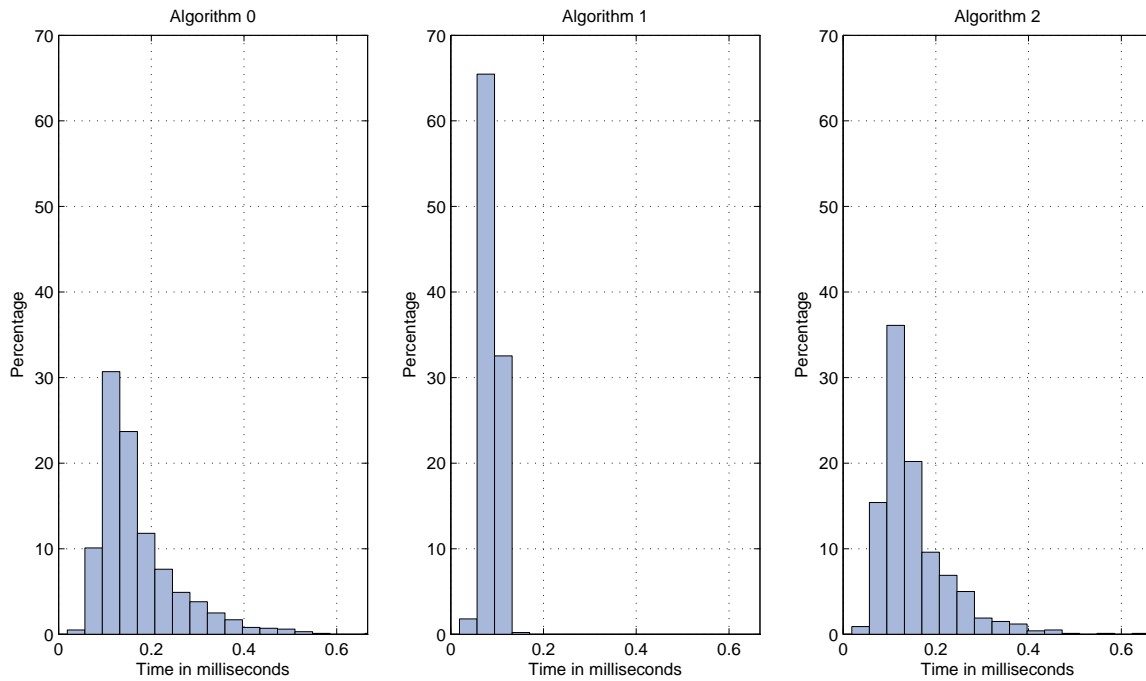
(b) 30° beamwidth

Figure 4-12: Time of arrival for the different forwarding algorithms and the different antenna beamwidths.

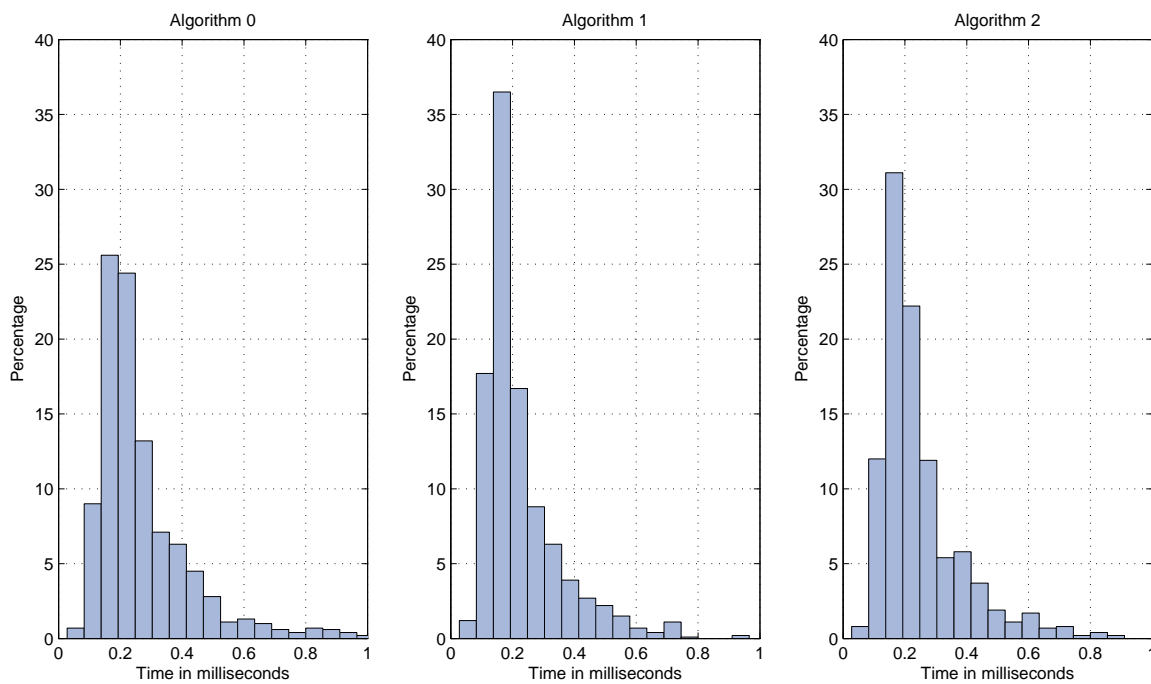
Table 4-4: Results for Simulation Set #3

Name	RTT in milliseconds			
	Mean	Std	Max	Min
H4_A0_60D_M1	0.1699	0.0873	0.7117	0.0435
H4_A1_60D_M1	0.0873	0.0158	0.1416	0.0491
H4_A2_60D_M1	0.1526	0.0754	0.7557	0.0424
H4_A0_30D_M1	0.2712	0.1540	1.0665	0.0606
H4_A1_30D_M1	0.2257	0.1258	0.9123	0.0557
H4_A2_30D_M1	0.2479	0.1364	1.1034	0.0656

**Figure 4-13:** The mean delay for Simulation Set #3.



(a) 60° beamwidth

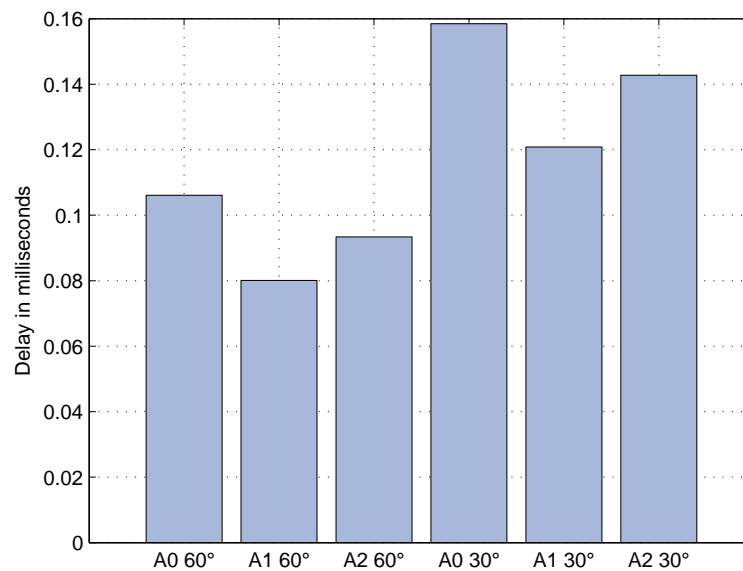


(b) 30° beamwidth

Figure 4-14: Time of arrival for the different forwarding algorithms and the different antenna beamwidths for Simulation Set #3.

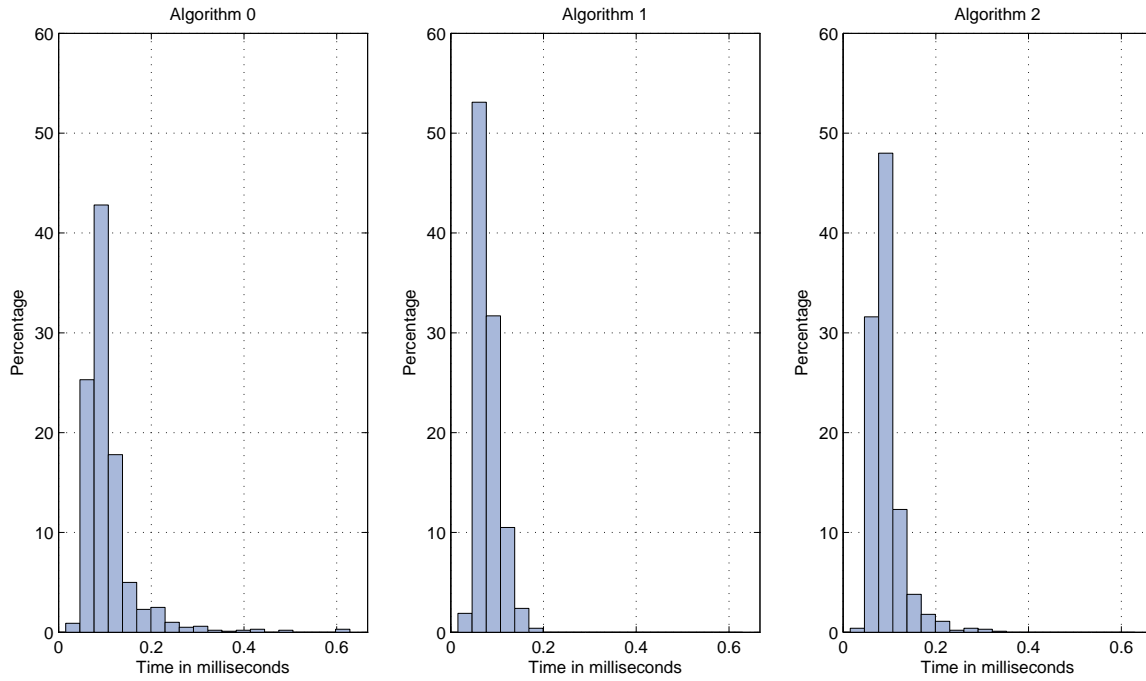
Table 4-5: Results for Simulation Set #4

Name	RTT in milliseconds			
	Mean	Std	Max	Min
H4_A0_60D_M2	0.1061	0.0582	0.6131	0.03072
H4_A1_60D_M2	0.0801	0.0237	0.1791	0.0354
H4_A2_60D_M2	0.0933	0.0341	0.3373	0.0411
H4_A0_30D_M2	0.1585	0.0953	0.9215	0.0462
H4_A1_30D_M2	0.1208	0.0514	0.7865	0.0490
H4_A2_30D_M2	0.1428	0.0772	0.6886	0.0426

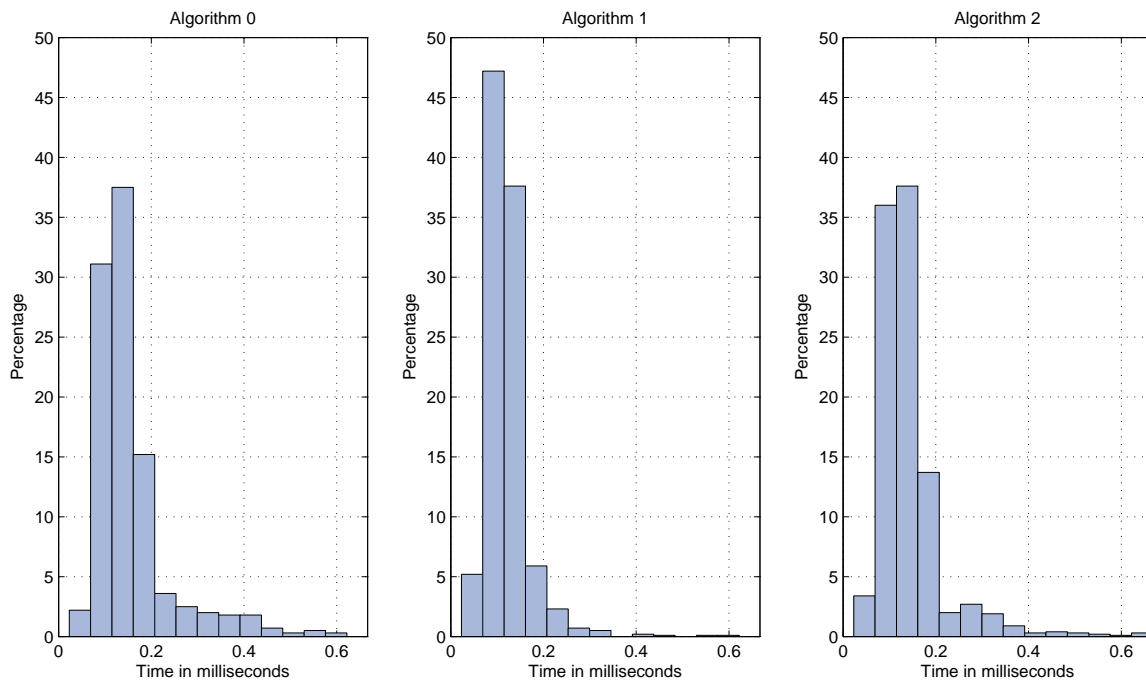
**Figure 4-15:** The mean delay for Simulation Set #4.

that the node degree, thus the number of neighbours increases. This increase of neighbours also leads to a higher number of shortest path. In stead of only one shortest path like Simulation Set #3, Simulation Set #4 contains thirteen shortest paths of four hops. This network topology is named **Mesh Network #2**. The results of the simulation are put in Table 4-5. Figure 4-15 and Figure 4-16 show the mean RTT and the times of arrival respectively.

From the Figure 4-15 it can be seen that the increase of the mean node degree has lead into shorter RTTs compared with Mesh Network #1. Compared with Simulation Set #2 the mean times are comparable. The maximum RTT of Simulation Set #4 is nevertheless substantially higher. Furthermore the RTTs are not normally distributed anymore.



(a) 60° beamwidth



(b) 30° beamwidth

Figure 4-16: Time of arrival for the different forwarding algorithms and the different antenna beamwidths for Simulation Set #4.

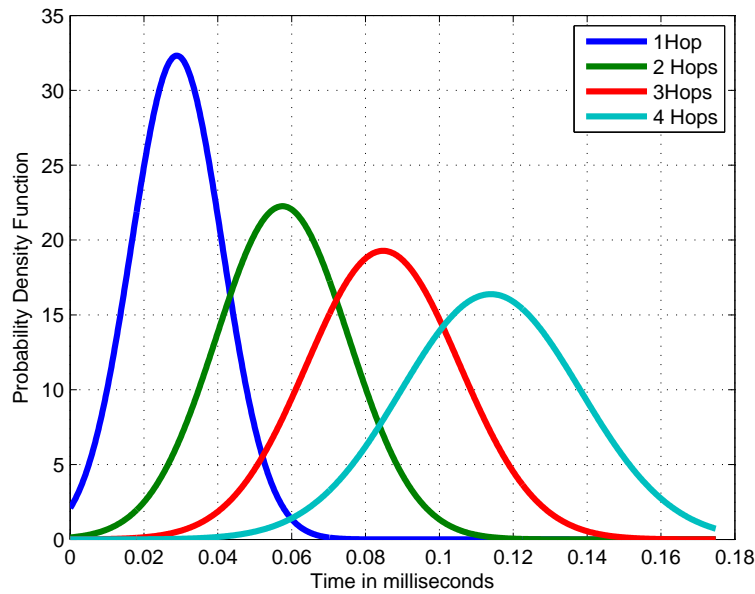


Figure 4-17: Fitted normal distributions for the different hops. All the times are for a straight line configuration.

4-3-5 Fitted Normal Distributions

The histograms for Simulation Set #1 and Simulation Set #2 show the behaviour of normal distributions. To compare the results better in one figure the next formula is used to fit curves to the distributions.

$$f_T(t) = \frac{1}{\sqrt{2\pi}\sigma^2} e^{-(t-\mu)^2/\sigma^2} \quad (4-1)$$

Here the Probability Density Function (PDF) is given by $f_T(t)$, it is dependent on the time, t . The standard deviation and mean are given by σ and μ respectively. Figure 4-17 shows the normal distributions for Simulation Set #1. The values for the mean and standard deviation are taken from Table 4-2. Using Table 4-3 the results for Simulation Set #2 are fitted to normal distributions, given in Figure 4-18.

4-4 Simulation Conclusions

- **Number Of Hops** Simulation Set #1 shows the influence of the number of hops on the RTT best. The time needed for route request is linearly dependent upon the number of hops. As the number of hops increase the mean RTT increases. Furthermore, a rise in the number of hops has an increasing effect on the standard deviation of the RTT. This means that the route requests are spread out more over time. Figure 4-17 shows fitted normal distributions to the results given in Table 4-2.

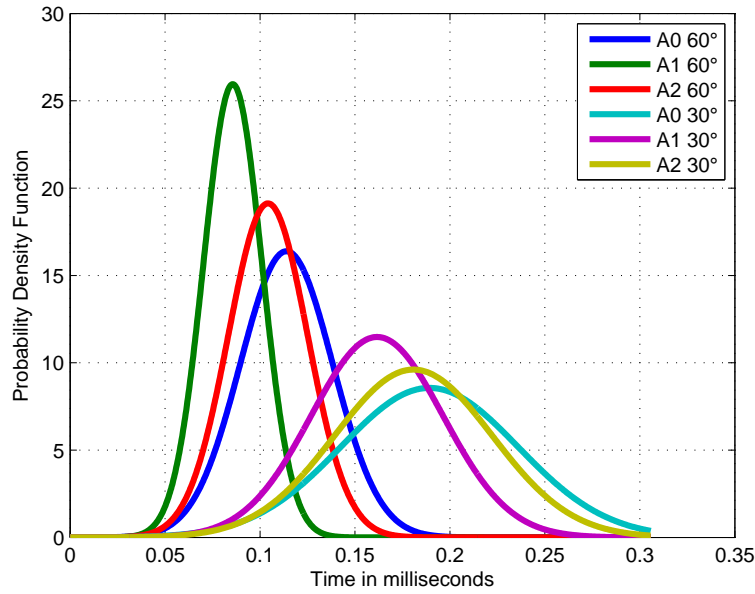


Figure 4-18: Fitted normal distributions for the time of arrival for different forwarding algorithms and antenna beamwidths. All the times are for a straight line configuration of four hops

Here shifting (increasing mean) and spreading (increasing standard deviation) of the time can easily be seen.

- Forwarding Algorithm** Using an optimisation forwarding algorithm can improve the performance of route discovery process. Algorithm 1 has a better performance, in the sense that it has shorter mean times and shorter standard deviations. Algorithm 2 performs second best. Figure 4-18 depicts normal distributions obtained by using the values given in Table 4-3. It should be noted that the performance of the forwarding algorithms depends heavily on the topology. The shortest path for all the scenarios was a straight line. Should this not be the case, Algorithm 1 may be failing.
- Antenna Beamwidth** From comparing the 60° antenna beamwidth and 30° antenna beamwidth in the simulation sets, it can be said that a larger beamwidth leads to a shorter RTT. Doubling the beamwidth almost leads to halving the mean time. This is logical since doubling the beamwidth leads to halving the number of transmissions. The use of optimisation forwarding algorithms have less effect on smaller beamwidths compared with larger beamwidths. It should be noted however that the results depend heavily on the chosen scenarios. The scenarios given here were executed with no other traffic going on. The higher spatial diversity resulting from smaller beamwidth could not be exploited in the scenarios. With on going traffic and a smarter forwarding algorithm, like transmitting only in directions of known neighbours, smaller beamwidths may have better performance. Another important

feature of using smaller beamwidths, the increasing transmission range, was not taken advantage of in the simulation sets.

- **Mean Node Degree** The mean node degree is not directly related to the RTT. However the number of shortest paths has an important relation with the RTT. Networks with a multiple shortest paths performs better compared with networks with a single shortest path. The probability of finding a shortest path increases with an increasing mean node degree. But in case there is only one shortest path, a higher mean node degree leads to a higher delay.
- **Mathematical Model** The simulations show the same behaviour as the mathematical model. The values for the straight line topology are almost the same as the values resulting from the mathematical model. Furthermore, the average RTT for the simulations with a mesh network are about the average RTT from the extended model.

Conclusions

The 60 GHz mmWave WPAN has a promising feature to provide ultra high data rate wireless links, supporting transmission of HDTV signals. Although 60 GHz is not suited for long range communication due to atmospheric absorption, high path loss and attenuation by various objects, it is very well suited for WPANs. This kind of network does not cover a large area. The short range and the high attenuations for example by walls make the WPANs also more secure, because of less overhearing by unwanted devices.

The 802.15.3 MAC protocol is designed specifically to support high data rate WPANs. The TDMA structure of the CTAP makes it possible to support QoS. Nevertheless combining the mmWave technology with the 802.15.3 MAC imposes some challenges. One of the main factors for link failure is the fluctuations in the channel caused by movement of humans. Therefore a solution has been proposed in this thesis.

5-1 Conclusion

The goal of this thesis is devising a method for anti blocking for the 60 GHz mmWave WPAN. A multi-hop solution is used to resume connection. To achieve this the 802.15.3 MAC protocol was edited to support directional antennas and a scheme was developed for two devices with a lost connection to reconnect.

The anti blocking proposal uses a multi-hop solution to reconnect devices which suffer from blocking. In order to overcome blocking between two communicating devices, the next steps are taken:

1. **Detection of shadowing.** Shadowing or blockage of the link can be detected using an acknowledgement scheme. The acknowledgements are used as feedback to check

if a message has arrived at the receiver. A frame is retransmitted when it is not acknowledged. After three missing acknowledgement the channel is assumed to be blocked. Another method of detecting blockage is by looking at the RSSI. When blocking occurs the drop in signal power is graduate. This means that it can be predicted if the channel is going to be blocked when the RSSI drops to a certain level.

2. **Initialising route discovery.** When the blockage of the channel is detected. The transmission pair needs to initialise a route discovery process in order to find a suitable route between the two devices. The RREQ message is broadcast using directional antennas. Using the direction-of-arrival of the RREQ message a RREP message is unicast along the network.
3. **Resuming connection.** To resume connection the intermediate devices found during the route discovery process are used for multi-hop communication. Two situations may occur.
 - If the all the nodes used are within the same piconet, the intermediate nodes are used to forward data.
 - If one of the nodes is outside of the piconet, a logical piconet has to be formed. A logical piconet is a network containing multiple piconets which are aligned. This means that the channel is scheduled in a way that the different piconet do not interfere with each other. Within the logical piconet all devices needed for communication form a piconet. Within this piconet the intermediate devices are used to forward data.
4. **Detecting if channel is available.** When the channel between two devices which suffer from shadowing is available these two devices should reconnect using the direct path. Forwarding traffic is less efficient compared with direct communication.

By calculating the delay, the performance of the route discovery process can be measured. First a mathematical model for this delay is derived. Next simulations were run to validate the mathematical model.

The goals of the mathematical model and the simulation are the following:

- To see the influence of the number of hops on the RTT. The mathematical model and the simulation both show that an increasing number of hops leads to an increasing RTT. Moreover, the mathematical model shows a linear behaviour for a change in the number of hops. This trend is also seen for the simulation.
- To check the influence of the antenna beamwidth on the RTT. Both the mathematical model and the simulation assume the nodes are operating in a room. Because of the small wavelength 60GHz radio has, the radio waves cannot penetrate walls well. This means that for the mathematical model and the simulation the transmission range is

not increased using a smaller beamwidth. Under this assumption it can be observed that smaller antenna beamwidths lead to a higher RTT.

- To verify The influence of the mean node degree on the RTT. When there is only one shortest path the mathematical model as well as the simulation show that in increasing network leads to an increasing average RTT. The simulation shows that if there are multiple shortest paths, the average RTT becomes lower compared with the minimum number of nodes with one shortest path.
- The influence of the forwarding algorithm on the RTT. The mathematical model shows a dependency of the average delay for route discovery on the number of directions to transmit to. As the number of directions increase, the average RTT also increases. In the simulation smart forwarding algorithms were also used to see if this could lead to a better performance. Simulations have shown that using Forwarding Algorithm #1 leads to an increased average RTT. The decrease in RTT is more noticeable for larger beamwidths. It should however be noted that this forwarding algorithm was only simulated for a straight line network and a grid network. When the topology is different, the forwarding algorithm may worsen the performance.

Another very important conclusion that can be drawn from the mathematical model and the simulation is that the time average time needed for route discovery is far below the medium durations for shadowing given in [14]. In [14] the median of the duration vary from 100 milliseconds for one to five persons with a threshold of 20 dB, up to 450 milliseconds for 11 to 15 persons with a threshold of 10 dB.

5-2 Future Work

For future work mobility of nodes could be considered. The simulations done in OPNET Modeler® all assumed static wireless nodes. In real life WPANs nodes are not static but mobile. The solution proposed in Chapter 2 should be able to cope with mobile nodes. It is there for interesting to see what the performance under mobile nodes is.

The mathematical model is derived from the assumption that all the nodes in the network have data from a higher layer to transmit. During the CAP not the most vital data is transmitted. The CAP is mainly used channel time reservations. Not every node needs to reserve a time slot for peer-to-peer communication. This means that the assumption of saturated traffic may be too strict. A mathematical model that does not assume saturated traffic, would be more realistic.

Another interesting item for future work is using neighbour discovery to optimise the forwarding algorithm. With smaller beamwidth the probability that the direction of transmission of an RREQ message does not have any receivers is larger compared with larger beamwidths. This transmission is redundant and adds up to the route discovery delay.

When the transmitting node keeps track of the location of all the neighbours, transmitting only in the direction of neighbours would keep redundant transmissions to a minimum. Furthermore if neighbours change their direction to the transmitting node, and the transmitting node still has the old direction in the neighbour-list, the RREQ transmission will still be redundant. Therefore this forwarding algorithm needs smart ways to discover neighbours and communicate with them.

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